23992

National Library of Canada | Bibliothèque nationale du Canada

CANADIAN THESES ON MICROFICHE | THÈSES CANADIENNES SUR MICROFICHE

NAME OF AUTHOR/*NOM DE L'AUTEUR* MICHAEL BRISTOL

TITLE OF THESIS/*TITRE DE LA THÈSE* A METHOD TO DETERMINE FLOOD HYDROGRAPHS FOR UNGAUGED WATERSHEDS

UNIVERSITY/*UNIVERSITÉ* ALBERTA

DEGREE FOR WHICH THESIS WAS PRESENTED/*GRADE POUR LEQUEL CETTE THÈSE FUT PRÉSENTÉE* M.Sc.

YEAR THIS DEGREE CONFERRED/*ANNÉE D'OBTENTION DE CE GRADE* 1975

NAME OF SUPERVISOR/*NOM DU DIRECTEUR DE THÈSE* DR. J. P. VERSCHUREN

Permission is hereby granted to the NATIONAL LIBRARY OF CANADA to microfilm this thesis and to lend or sell copies of the film.

The author reserves other publication rights, and neither the thesis nor extensive extracts from it may be printed or otherwise reproduced without the author's written permission.

L'autorisation est, par la présente, accordée à la BIBLIOTHÈQUE NATIONALE DU CANADA de microfilmer cette thèse et de prêter ou de vendre des exemplaires du film.

L'auteur se réserve les autres droits de publication; ni la thèse ni de longs extraits de celle-ci ne doivent être imprimés ou autrement reproduits sans l'autorisation écrite de l'auteur.

DATED/*DATÉ* 21 APRIL 1975 SIGNED/*SIGNÉ* M Bristol

PERMANENT ADDRESS/*RÉSIDENCE FIXE* L1802, 1600 BEACH AVE.
VANCOUVER B.C.
V6G 1Y6

THE UNIVERSITY OF ALBERTA

A METHOD TO DETERMINE FLOOD HYDROGRAPHS FOR UNGAUGED WATERSHEDS

BY

M. BRISTOL

A THESIS

SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH

IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE

OF MASTER OF SCIENCE

DEPARTMENT CIVIL ENGINEERING

EDMONTON, ALBERTA

(SPRING), (1975)

© M. Bristol 1975

ABSTRACT

A method was derived to determine the approximate hydrograph shape for ungauged watersheds located in Alberta and southern Yukon Territory. The published discharge data for each of 70 gauged watersheds was analysed by computer to determine the most rapid rates of change of average daily flow at every discharge level within the measured range. The most rapid rates of rise and fall were plotted as logarithims of discharge versus time in the form of single-peak, composite hydrographs. The hydrograph limbs were approximated by straight lines and a realistic baseflow discharge determined from each graph.

A number of topographical and meteorological parameters were determined for each of the 70 watersheds, and regression equations established using, in turn, the maximum rates of rise and fall and baseflow discharge as dependent variables, in a step-wise multiple linear regression analysis.

An idealised hydrograph was constructed for each of the 70 watersheds, based on the maximum rates of rise and fall and baseflow discharge previously determined, and representing a particular volume of direct runoff. This led to the derivation of an equation relating peak flow to the depth of excess precipitation over the basin and to the idealised-hydrograph characteristics. The equation was used to compute an expected peak flow for each of the study watersheds, for depths of excess precipitation ranging from 0.1 to 10 ins. Regression equations were obtained, relating peak flow for each depth of excess precipitation to the topographical and meteorological characteristics of the watersheds.

The equations were simplified into one expression relating peak flow to depth of excess precipitation and drainage basin area. This

expression was then refined to take account of hydrograph shape. The expressions derived from the study allow the determination of the approximate shape of the hydrograph resulting from a given depth of excess precipitation for an ungauged watershed. A knowledge of certain readily available basin characteristics is required and the method is applicable only to the region from which the sample was derived, and for basins up to 15,000 sq. miles in area.

ACKNOWLEDGEMENTS

The author wishes to thank Dr. J.P. Verschuren for his help and guidance throughout the study. Thanks are also due to the Research Council of Alberta for their financial support, and to the Department of Indian Affairs and Northern Development who provided the opportunity to collect data from certain small watersheds.

The author also wishes to thank the members of staff, academic and non-academic, of the Department of Civil Engineering, University of Alberta, without whom preparation of this thesis would not have been possible.

TABLE OF CONTENTS

CHAPTER		PAGE
1.	INTRODUCTION	1
	General	1
	Objectives	2
	Factors Affecting Hydrograph Shape	3
	Maximum Hydrograph Slopes	6
	Watersheds Included in Study	8
II.	COMPOSITE HYDROGRAPHS	
	Method of Preparing Composite Hydrographs	11
	Program "SLOPE"	12
	Program "ADD"	16
	Hydrograph Parameters	17
III.	THEORY OF CORRELATION AND REGRESSION	
	Correlation Between Two Variables	22
	Linear Regression	23
	Measures of Multiple Linear Correlation	24
	'Independent' Variables	26
	Stepwise Multiple Linear Regression	27
	Confidence Intervals on Estimated Values	29
IV.	REGRESSION ANALYSIS	
	Watershed Characteristics Used as Independent Variables	30
	Regression Analysis & Results	34
	Map Coefficients	43
	Regional Analysis	46

CHAPTER PAGE

V. PEAK DISCHARGE

Theory 51

Regression Analysis With Peak Flow as Dependent Variable.. 55

Peak Discharge vs. Topographic Drainage Area 59

Comparison with Existing Peak Flow formulae 68

VI. DISCUSSION & CONCLUSIONS

Discussion 71

Procedure to Determine Hydrograph Shape for Ungauged Watersheds 76

Conclusions 77

Suggestions for Further Study 78

BIBLIOGRAPHY 80

* * * *

APPENDIX I COMPUTER PROGRAMMES 82

APPENDIX II HYDROGRAPH PARAMETERS 93

APPENDIX III DRAINAGE BASIN CHARACTERISTICS 100

APPENDIX IV MAP COEFFICIENTS FOR R (av), K (av), BF AND PEAK FLOW 115

LIST OF TABLES

Table	Description	Page
1	Drainage Basin Characteristics	31
2	Results of Stepwise Linear Regression Analysis with R(av) as Dependent Variable	36
3	Final Results of Regression Analysis with K(av) and BF. as Dependent Variables	44
4	Multiple Linear Regression Analysis for R(av) for Alberta Stations by Regions	50
5	Regression Equations of Peak Discharge for Various Depths of Excess Precipitation	57
6	Regression Equations for Peak Discharge vs. Topographic Drainage Area	58
7	Bi-variate Distribution of R and K for 65 Sample Gauging Stations	65
8	Regression Equations of Peak Flow vs. Topographic Drainage Area, for Ranges of R and K	66

LIST OF FIGURES

Figure		Page
1	Typical Hydrograph From a Single Storm	4
2	Illustration of Method of Hydrograph Composition .	14
3	Typical Rising Limb of Composite Hydrograph Showing Two Measures of its Steepest Slope	20
4	R(av): Observed vs. Estimated Values by Regression	47
5	K(av): Observed vs. Estimated Values by Regression	48
6	B/FLW: Observed vs. Estimated Values by Regression	49
7	Idealised Hydrograph Shape	52
8	Regression Intercept vs. Depth of Excess Precipitation	60
9	Peak Flow from 1 ins Excess Ppt: Observed vs. Estimated Values by Regression.	61
10	Peak Flow from 1 ins Excess Ppt: Estimated Values by Regression, Adjusted Using Map Coefficients	62
11	Estimated Peak Flow from 1 ins Excess Precipitation vs. Topographic Drainage Area	63
12	Peak Flow from 1 ins of Excess Ppt. vs. Topographic Drainage Area, for Ranges of R and K	67
13	Maximum Depth of Ppt. vs. Area: Storm June 19-29 1969, Near Banff, Alberta	69

CHAPTER I

INTRODUCTION

1.1 General

Before hydrographs of ungauged watersheds can be determined, the hydrographs of gauged watersheds must first be quantified, and relationships established between the parameters which describe hydrograph shape and other parameters which would be available for ungauged watersheds, for example, the physical characteristics of the basin.

As early as 1930, attempts were made to represent a flood hydrograph of a particular river by one graph (referred to as the T-hour unit hydrograph) with excess precipitation as the only variable, and it was accepted that the effect of all physical characteristics of the drainage basin were incorporated in this graph. Later, the instantaneous unit hydrograph was developed in order to eliminate the parameter T (the duration of the uniform excess precipitation).

The unit hydrograph is used to determine flood hydrographs resulting from severe storms through the simple procedure of superposition, in spite of the fact that the assumptions on which it is based are questionable. A limitation of the use of the unit hydrograph is that preparation requires detailed knowledge of the duration of the precipitation which caused the direct runoff. For many rivers, this information is not available and the unit hydrograph cannot be derived. Usually, the snowmelt hydrograph is different from the rainfall hydrograph.

There have also been attempts by Nash (1957), De Coursey (1966) and Gupta (1974) to develop and test a mathematical equation

to describe the shape of a surface runoff hydrograph. The attempts have achieved considerable success, but in order to evaluate the parameters of the equation for a particular basin, usually, at least one representative hydrograph from that basin is necessary. Thus, these mathematical representations of hydrograph shape cannot be derived for ungauged watersheds. It would be advantageous if characteristic watershed hydrographs could be represented by one or more numerical parameters to allow correlation with pertinent drainage basin characteristics through a regression analysis, so that the parameters could be derived for ungauged watersheds.

1.2 Objectives

The objectives of the study were as follows: -

1) To write a computer program to determine the greatest rates of change of discharge from a period of hydrometric record, and to plot a single peak hydrograph composed of the steepest sections so found.

2) To plot composite hydrographs for a number of selected gauged watersheds located in Alberta and southern Yukon Territory.

3) To approximate the rising and falling limbs of each composite hydrograph by straight lines. (The slopes of such lines could be used as a watershed classification system.)

4) To compute regression equations relating the slopes of the rising and falling composite hydrograph limbs to certain physical characteristics of the watershed.

5) To prepare idealized straight line hydrographs for each sample watershed, to determine a relationship between the peak discharge and the volume of direct runoff, and to correlate the peak flow with the physical characteristics of the watersheds.

6) Using the relationships of 4 and 5, to derive a method to determine basic hydrograph shape, for a given depth of excess precipitation, for ungauged watersheds.

1.3 Factors Affecting Hydrograph Shape

The shape of a hydrograph resulting from a single, short-duration storm distributed uniformly over the drainage area follows a general pattern; a rising portion, a crest segment and a falling portion (Fig. 1). The shape is influenced by climatic factors and by the topographical and geological features of the basin. If the input were distributed uniformly over the basin, then the shape of the rising limb would be dependent upon the intensity and duration of the input. However, it is generally assumed that the recession limb would be virtually independent of the storm characteristics since it represents the withdrawal of water from storage in the basin, after input has ceased. The shape of the recession limb is almost solely dependent upon the physical features of the basin (Gray 1970). Ideally, for a particular watershed, if no further input takes place after the cessation of uniformly areally-distributed input, the recession portion of the hydrograph, from any particular discharge value, will be the same, regardless of the shape of the rising limb. The time base of the rising limb is definitely influenced by the duration of the input. (Linsley 1949).

For large basins in particular, it would be most unlikely for input to be distributed uniformly over the basin, therefore the hydrograph shape is influenced by the areal distribution. In general, input concentrated near the basin outlet will produce steeper rising and recession limbs and a greater peak flow for a given volume of excess precipitation, than if the same volume were uniformly, areally distributed.

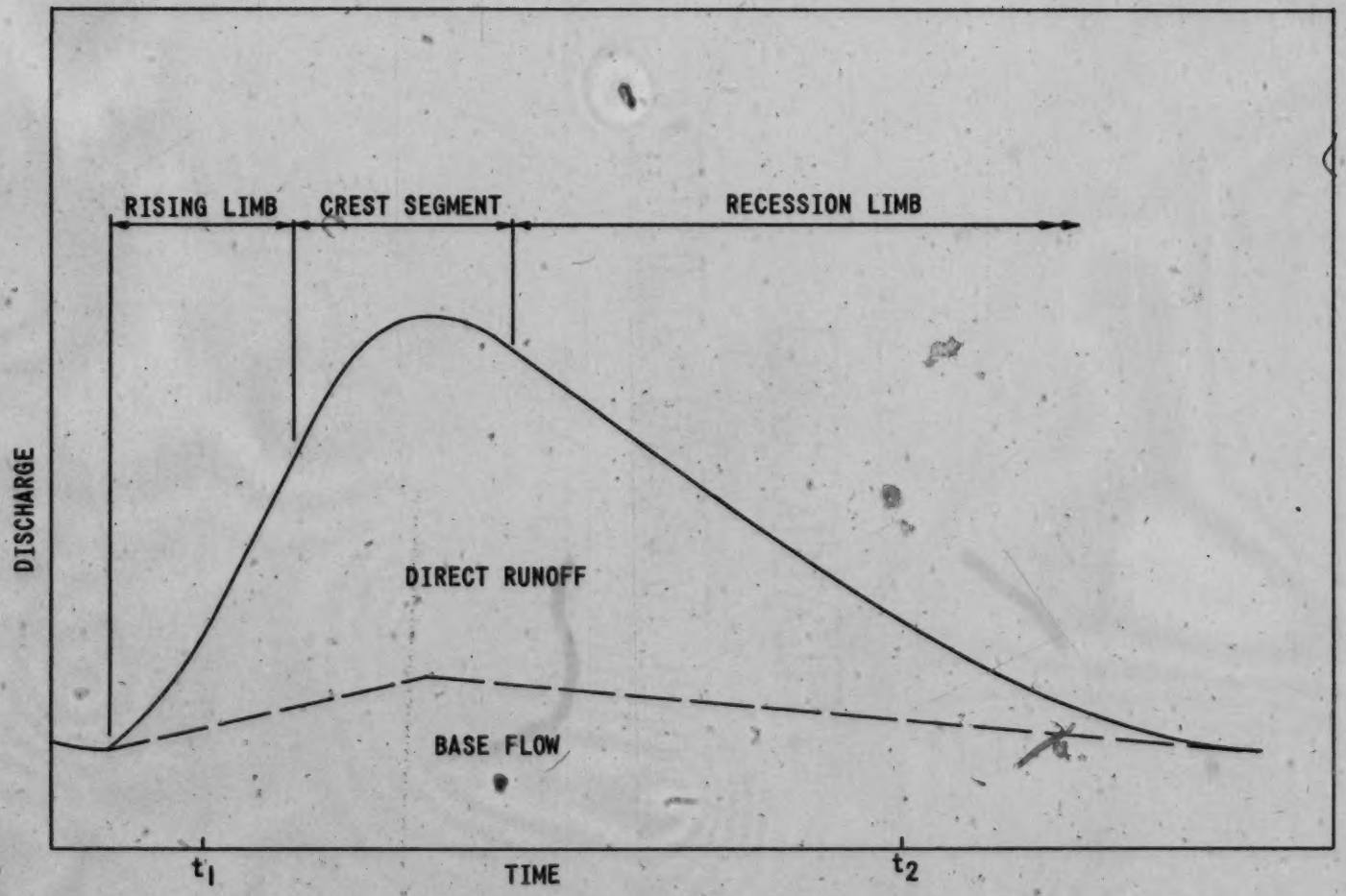


FIG. 1 TYPICAL HYDROGRAPH FROM A SINGLE STORM

The rising limb of a typical hydrograph is concave upwards, due to the decreasing proportion of precipitation 'lost' to infiltration, interception and depression storage as the storm progresses. In addition, drainage basins tend to be approximately pear-shaped so that the area between isocrones is greatest in the middle and upper portions of the basin. Thus, uniform input over a basin produces an increasing rate of discharge.

The recession limb is also typically concave upwards since it represents the exponential decay of the flood wave.

The area under a hydrograph between two points in time, t_1 and t_2, (Fig. 1) represents the volume of runoff in that time interval. Generally, such a runoff volume has two components; direct runoff and base flow runoff. Direct runoff is basically water which reaches the stream channel by flowing over, or more usually through, the soil mantle; while base flow is water supplied from the saturated area below the groundwater table.

Base flow discharges remain relatively constant compared to direct runoff discharges, for the duration of direct runoff, and it is useful to separate direct runoff from baseflow. Many separation methods are in current use but all involve a large measure of subjectivity. There can be no exact separation since the physical change from direct flow to baseflow is transitional. However, a separation line on a hydrograph can usually be drawn to produce a sensible division into direct runoff and baseflow.

It is apparent from Fig. 1 that for a given volume of direct runoff, the greatest peak discharge will occur when the rising and falling limbs are steepest. A steep rising limb will result from intense input,

particularly if it is concentrated near the basin outlet, and a steep falling limb will be produced when there is no further input during the recession period.

1.4 Maximum Hydrograph Slopes

It is generally accepted that there is a limit to the intensity and duration of rainfall which can possibly occur over a particular area. The limiting combination produces the Maximum Probable Storm. The assumption that there is a limit to the combination of meteorological factors which produce rain, can be extended to cover depth of snowpack and melt-rate. Thus, we can assume that there exists a maximum possible rate of input at any particular site. The Maximum Probable Flood, produced as a result of these extreme input rates over a drainage basin, theoretically has a return period of infinity (Koelzer and Bitoun 1964), and therefore will not have occurred during any period of stream gauge records. However, it is quite possible that maximum intensities have been reached for short durations, or have occurred over portions of basins, for example, near the outlets, so that maximum rates of rise may have been achieved, or at least approached, for short periods during different flood events. By combining the maximum rates of rise of portions of various hydrographs, the rate of rise corresponding to a rare flood event may be approximated.

A number of methods exist to determine the steepest limbs of hydrographs from gauged basins but they are not completely satisfactory.

The simplest method is to take the rising and falling limbs directly from a single large flood hydrograph, preferably one resulting from an intense input. An improved method is to determine the slopes of the limbs of several flood hydrographs and select the steepest one.

The limitations of such a method are: -

i) that it is unlikely that input conditions remained constant for the duration of the rising limb, and

ii) it cannot be known whether the slopes are the steepest possible.

An improved method is to build up a hydrograph covering the entire discharge range of the record, by selecting the steepest slope which has occurred at every discharge value. The resulting hydrograph limbs are thus a synthesis of parts of different flood hydrographs, and consist of those portions occurring when conditions producing rapid rates of rise and fall were most extreme. A problem with this method is that to obtain the slopes accurately, the hydrograph must be drawn to a large time scale resulting in extremely long and cumbersome plots.

A statistical analysis of the falling limb values (Verschuren 1970) was presented in the form of plots of discharge on one day Q_n vs. discharge on the following day Q_{n+1}. Data for these plots was obtained where the hydrograph crossed preselected levels of discharge Q_d, such that $Q_{n+1} > Q_d > Q_n$. For the data at each discharge level, the gradient of the graph was computed and the Q_n and Q_{n+1} values corresponding to the median, the tenth percentile and the nintieth percentile of the gradient were plotted.

It was recognized that the computer analysis was not satisfactory in many cases because some detail was missed by using preselected discharge levels, and more important, the output did not allow a subjective look at the hydrograph shape.

The first objective of this study was to write a computer program that would calculate the co-ordinates of a hydrograph, composed

of the steepest rising and falling portions of a discharge record at a station, and which covered the entire discharge range. The hydrograph could then be plotted to any desired scale so that realistic slopes of the limbs could be assessed. A description of the method used to obtain such composite hydrographs is given in Chapter 2.

1.5 Watersheds Included in Study

In Alberta, as in most other areas, a disproportionate number of large watersheds are permanently gauged, resulting in a lack of information on smaller watersheds (less than 200 sq. miles in area). A knowledge of expected peak discharges on small watersheds is essential for the economical design of an increasing number of stream crossings and other fluvial structures. The absence of direct streamflow measurements could be largely overcome if hydrograph parameters from gauged watersheds could be correlated with their respective basin physical characteristics. The resulting relationships could then be used to predict hydrograph parameters from a knowledge of the basin characteristics alone.

Discharge data published by Water Survey of Canada is in the form of mean-of-the-day values. These are evaluated by determining the average gauge height for each day and selecting, from the station rating curve, the discharge associated with that gauge height. For a large watershed, where the rates of change of discharge are small, the hydrograph prepared from mean-of-the-day values is close to that prepared from instantaneous discharge values. For a small watershed, however where discharges are rapidly changing, the hydrograph resulting from mean-of-the-day values differs considerably from the hydrograph of instantaneous values, particularly in the region of discharge peaks and troughs. Thus,

completely erroneous hydrograph parameters can result from analysis of mean-of-the-day discharge hydrographs for small watersheds.

Since hydrographs derived from instantaneous data are not readily available, the present study is restricted to watersheds greater than 500 sq. miles. This figure was selected after comparisons were made of instantaneous and mean-of-the-day discharge hydrographs, for the same flood events, on basins ranging from 1 to 2,000 sq. miles. For basins of 500 sq. miles and greater, the slopes of rising and falling limbs of the mean-of-the-day discharge hydrograph closely approximated those of the instantaneous hydrographs.

As stated in Section 1.2, one objective of this study was to correlate parameters describing hydrograph shape with drainage basin characteristics. While appreciating that no drainage basin, however small, is entirely homogeneous in terms of slope, aspect, permeability, etc., it is apparent that the degree of homogeneity decreases with increasing basin area. It was considered desirable to use basins which, as far as possible, were located within one vegetation zone, e.g., prairie or boreal forest, so that such characteristics as Basin Latitude and 60 Minute Rainfall (see Section 4.1) were reasonably representative. An upper time limit to the size of basins included in the study was set at 15,000 sq. miles, which is a compromise between two considerations: -

i) to keep the basins small and therefore homogeneous

ii) to include in the regression analysis, as many basins greater than 500 sq. miles, as possible.

Sixty two watersheds were included in the analysis and each satisfied the following requirements: -

i) Discharge from the watershed had been measured for at least 10 years, either continuously or seasonally. (In areas where gauged watersheds were sparse, 7 years of record was accepted).*

ii) The watershed area was between 500 and 15,000 sq. miles. and iii) The location was such that it gave reasonably even distribution of gauging stations throughout the region of study.

In regions that required elimination of some stations in accordance with iii) above, preference was given to a watershed not situated within a larger one, already selected for study.

Forty-two watersheds in Alberta met the above requirements and were included in the study. The scope and accuracy of the analysis was enhanced by the inclusion of 20 watersheds (which also fulfilled the above requirements) situated in the Yukon Territory and for which the necessary data existed (Spence 1969). Thus, a total sample of 62 watersheds, for which reasonable periods of discharge records existed, were scrutinized and included in the regression analysis. (For station locations, see Appendix IV).

---

* The last year of record available for inclusion in the study was 1972.

CHAPTER 2

COMPOSITE HYDROGRAPHS

2.1 Method of Preparing Composite Hydrographs

A package of programs was written to produce the steepest hydrograph possible from the available hydrometric records of a particular gauging station, and plot the result on semilogarithmic co-ordinates. The whole of the hydrometric record may be used as input or it can be divided in 3 ways: -

i) chronologically: N consecutive years of data may be used, where N can range from 1 to the total number of years of record,

ii) by months: n consecutive months of data from each year may be included, where n can range from 1 to 12,

or iii) a combination of i and ii, i.e., part of the year for part of the period of record.

The first case is useful where the period of record is long and computer costs are to be minimized. The second case is useful when rates of rise and fall are known to be small, i.e., during winter months. In such a case the winter data can be omitted from the computations, again resulting in a considerable saving in computer costs.

The central program in the package is "SLOPE" which reads discharge values from magnetic tape (such as published by Water Survey of Canada). It is essential that the discharge data are equally spaced in time, for example daily or hourly. On an input file "Data", the

operator specifies the length of record to be used, and the first and last months of each year (n_1 and n_2) for which data is to be included.

Missing discharge values and discontinuities in the record are handled by the program so that no visual inspection of the input data is required.

Since the CPU time used by the program "SLOPE" (and hence the cost) is nearly proportional to the square of the number of discharge values included, it has been found economical to divide periods of record of greater than, about 7 years into 3 or 4 consecutive periods. The program "SLOPE" is called for each successive sub-period and produces the steepest hydrograph for that sub-period.

The 3 or 4 resulting hydrographs are combined by program "ADD", the output of which becomes the input for program "SLOPE"again, which then produces the required hydrograph co-ordinates for the whole period.

The co-ordinates of the final composite hydrograph are read by program "DRAW" which selects the logarithmic ordinate scale range, curtails the abscissor values, if necessary, to ensure that the plot length does not exceed 36 ins. and restricts the discharge axis length to 5 log-cycles. A plot is produced of a single hydrograph at an ordinate scale of 5.2 ins. per log-cycle and an arithmetic time scale of 1 ins. per day. The above ordinate scale was chosen so that the maximum discharge range which occurred on any one basin (5 log-cycles) just covered the maximum possible plot height of 26 ins.

2.2 Program "SLOPE"

The complete listing for program "SLOPE" is given in Appendix I. Discharge values on successive days are read by the program. If the discharge for a particular day is missing, the value is replaced by

-999.0. (Water Survey of Canada magnetic tapes are compiled using this system). To illustrate the method, the 23-day discharge record for which the steepest composite hydrograph is required, is plotted on semi-logarithmic axes (Fig. 2(a)).(In practice, the input data would not be plotted). It can be seen that discharge values for days 4, 5, 7 and 17 are missing (i.e., -999.0).

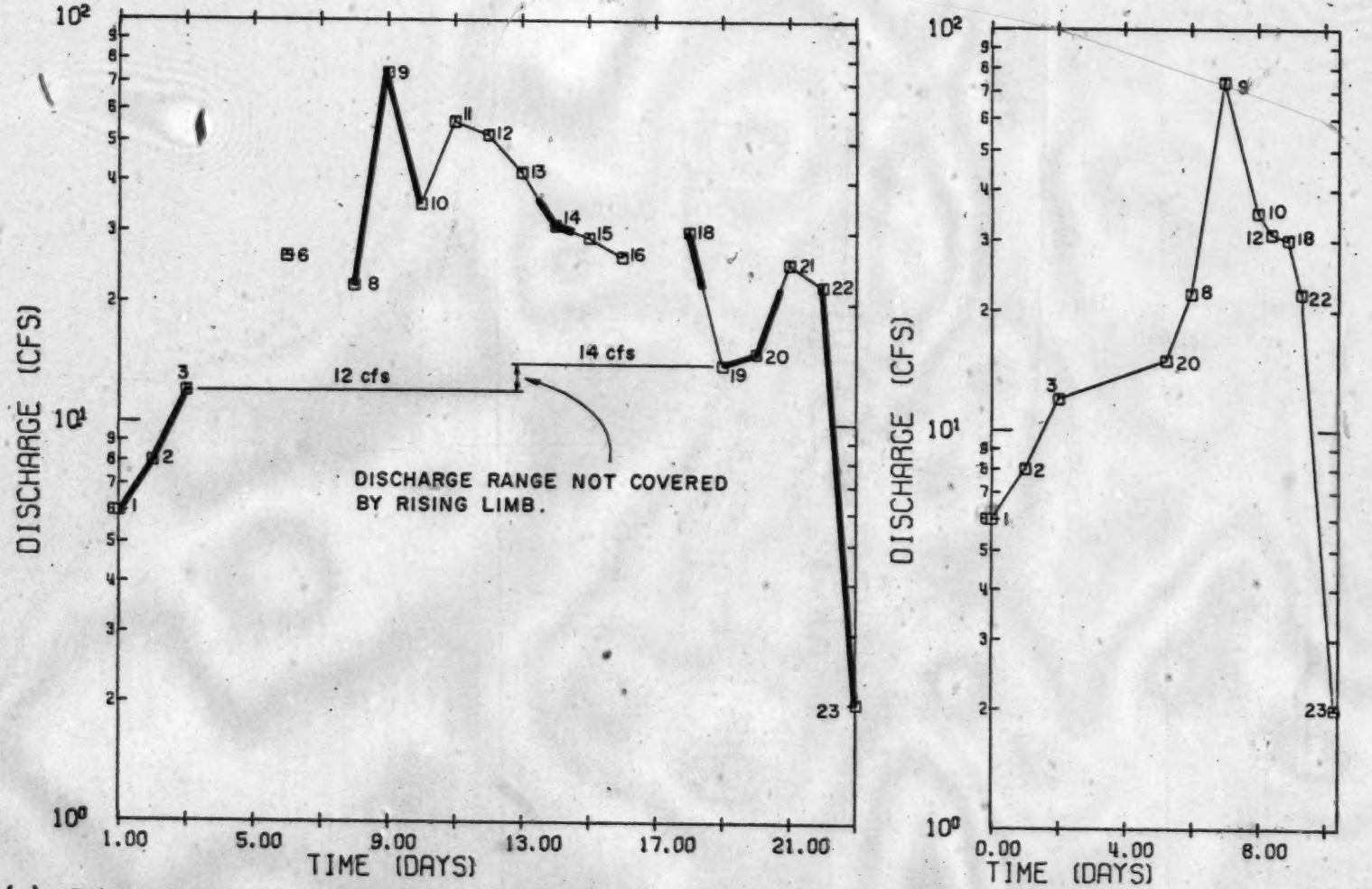
The required composite hydrograph (Fig. 2(b)) is composed of the heavy lines in Fig. 2(a) and was prepared as follows: -

The discharge values for the specified period are read into an array and their common logarithms calculated (from this point on, the program deals entirely with logarithms of discharge values). These values are arranged in descending order(points 9, 11, 12, 13, 10, etc.). Alongside each value, the discharge value occurring on the following day (when it exists) is listed (points 10, 12, 13, 14, 11, etc., respectively). This 2-dimensional array is separated into two further arrays:-

i) QP, containing pairs of values with a positive gradient e.g., point 10 - point 11, and

ii) QPAIR, containing pairs of values with a negative gradient e.g., point 9 - point 10 and point 11 - point 12.

A search procedure is then carried out, separately for the rising and falling limbs, commencing in each case with the maximum discharge value (point 9), and proceeding in descending order. For each successive value, those pairs of values from QP or QPAIR which span the discharge value under consideration are listed (e.g., for the rising limb, point 13, is spanned by lines 10 - 11 and 8 - 9). From each



(a) EXAMPLE OF DISCHARGE RECORD

(b) COMPOSITE GRAPH FROM STEEPEST SLOPES

FIG. 2 ILLUSTRATION OF METHOD OF HYDROGRAPH COMPOSITION

list the steepest gradient (line 8 - 9 for point 13) is selected and written into a further array together with the current spanned value (point 13).

A further gradient-comparing procedure results in 2 arrays; one for the rising limb, consisting of discharge values in ascending order, together with the steepest positive gradient preceding each value; and for the falling limb, an array consisting of discharge values in descending order together with the steepest negative gradient following each value. These arrays contain the necessary data to construct the rising and falling limbs of the composite hydrograph, as follows: -

The smallest discharge value on the rising limb, for which there exists a preceding line, is point 2. This value is given a time co-ordinate of t_1=1.0. The time co-ordinate for the second smallest discharge value on the rising limb (point 3) is determined by proceeding from point 2, at the gradient preceding point 3, until the value of point 3 is reached. The time interval so covered is added to t_1 to obtain t_2. The process is repeated until the maximum discharge is reached. The discharge value at t_o=0.0 is obtained by descending, for one day, at the gradient preceding point 2.

A similar process to that described above is used to compute the co-ordinates of the falling limb, starting from the peak value. The result is a list of co-ordinates composed of the steepest parts of the hydrograph which have occurred during the period of record. Finally, antilogarithms are taken of the discharge values in readiness for their being plotted on a logarithmic-scale, ordinate axis.

It can be seen from Fig. 2(a) that only part of the line 18- 19, for example, is heavy, and as such only the upper part appears in the hydrograph of Fig. 2(b). This is because, below the discharge value associated with point 22, the line 22 - 23 is steeper than line 18 - 19 and therefore appears in the final graph.

A situation may arise where the discharge record does not cover a certain discharge range, for example, in Fig. 2(a), the discharge range 12 to 14 cfs is not covered by the rising limb of the input record. In this situation, in order to simplify plotting of the output hydrograph, the line immediately above the 14 cfs. level (preceding point 20) is continued at the same slope across the gap, to 12 cfs. (point 3) as can be seen in Fig. 2(b).

Because of the above feature of the progr m, when a period of record is to be split by months, care should be taken to ensure that the discharge range covered by each limb is likely to be continuous. A typical annual hydrograph for a river with a peak in June should not, if possible, be divided into the two periods January to May and June to December. The hydrograph for the first half-year is predominantly rising while that for the second half is predominantly falling. This could lead to a discontinuous input record and resulting artificial slopes on the output hydrograph. A better division would be April to September and October to March.

2.3 Program "ADD"

A considerable saving in computer costs can result by dividing a long period of record into 3 or 4 (or 5) consecutive sub-periods. In such cases, calling program "SLOPE" for each sub-period results in the

output of the co-ordinates of the steepest hydrograph for each sub-period. These co-ordinates are then required to be read by program "SLOPE" to produce one final hydrograph. However, except for an extremely trivial case, the co-ordinates of the sub-period hydrographs will not be equally spaced in time, so that they cannot be directly read as input by program "SLOPE". This problem is overcome by calling program "ADD", which interpolates between the existing hydrograph co-ordinates, to produce a new set of discharge values spaced at half-day intervals. Some accuracy is lost by this process particularly near the hydrograph peak, but since the rising and falling limbs are reasonably straight, the interpolated co-ordinates adequately describe the original curve.

Program "ADD" operates on each sub-period in turn and joins the interpolated co-ordinates into a continuous record which can be read as input by program "SLOPE", to produce the co-ordinates for the single, final hydrograph for the entire period. When program "SLOPE" is required to read discharge values produced by program "ADD", the program "SLOPE" input parameter ADD, must be set equal to 1.0 (otherwise ADD=0.0).

2.4 Hydrograph Parameters

The foregoing method was used to produce a composite hydrograph for each of the 62 watersheds included in the study. The entire period of record for each gauging station was fed into the computer which plotted the required composite hydrographs to ordinate scales of 5.2 ins/log-cycle and abscissor scales of 1 ins/day. All hydrographs were plotted to the same scale to permit easy visual comparison.

One of the objectives of the study was to find the regression equations between the watershed characteristics as independent variables and the maximum rate of rise, maximum rate of fall and base flow dis-

charge, in turn, as the dependent variables; the dependent variables being determined from the computer-plotted composite hydrographs for each river gauging station included in the study.

This study is an attempt to demonstrate that maximum rates of rise and fall of hydrographs can sometimes be approximated by an equation of the form

$$Q = Q_o K^t$$

where Q = discharge at time t

Q_o = discharge at time t=0

and K = a constant

If such a relationship exists, then a plot of time versus the logarithm of discharge (or time vs discharge plotted on semi-logarithmic paper) results in a straight line, whose slope can be described by the constant K (For fuller analysis, see Section 5.1).

An inspection of the 62 composite hydrographs showed that the rising and falling limbs could, in general, be approximated by an equation of the form $Q = Q_o K^t$, since the rising and falling limbs were often straight over a range of discharges of several log cycles, and in some instances were practically straight over the entire discharge range. In many cases, where the lines were not straight, there were sections of the line distributed throughout the discharge range which were virtually at the same, maximum slope. It will be recalled that the composite hydrographs do not represent one flood event, but rather, are comprised of sections of several flood events which had occurred during the (often limited) period of record. If a limiting slope were to exist, then it would be expected that, as a longer period of record became available, more sections of the line would tend towards that maximum,

limiting slope.

A factor which could contribute to non-linearity of the rising and falling limbs, is the fact that in the lower discharge range, floods of that magnitude are more numerous, providing a greater sample from which to choose the steepest slope. If a limiting slope exists, it will probably occur in the lower and intermediate discharge ranges. Unless the observed maximum discharge rate occurred more than once during the period of record, the peak of the composite hydrograph will be an exact replica of the peak of that maximum flood. (This was shown to be the case in many instances).

Two measures of slope, for each limb, were determined from the composite hydrograph of each study watershed:

i) $R'(max)$ = the steepest slope which occurred for a significant discharge range (e.g., more than 1 log-cycle)

and ii) $R'(av)$ = an average slope between $R'(max)$ and a steep slope which recurs in several discharge ranges.

Fig. 3 shows a typical rising limb of a composite hydrograph and illustrates the method. Section CD has the steepest slope over a significant discharge range and hence its slope is taken as $R'(max)$. Sections AB, DE and FG have approximately the same slope so that $R'(av)$ is taken as an average between $R'(max)$ and the slope of section DE. It is assumed that if the period of record were longer, the slopes of sections BC and EF would approximate $R'(av)$. The method is highly subjective and many possible values of R' could be selected. However, the above procedure allowed the selection of "an average steepest slope" with a reasonable degree of consistency.

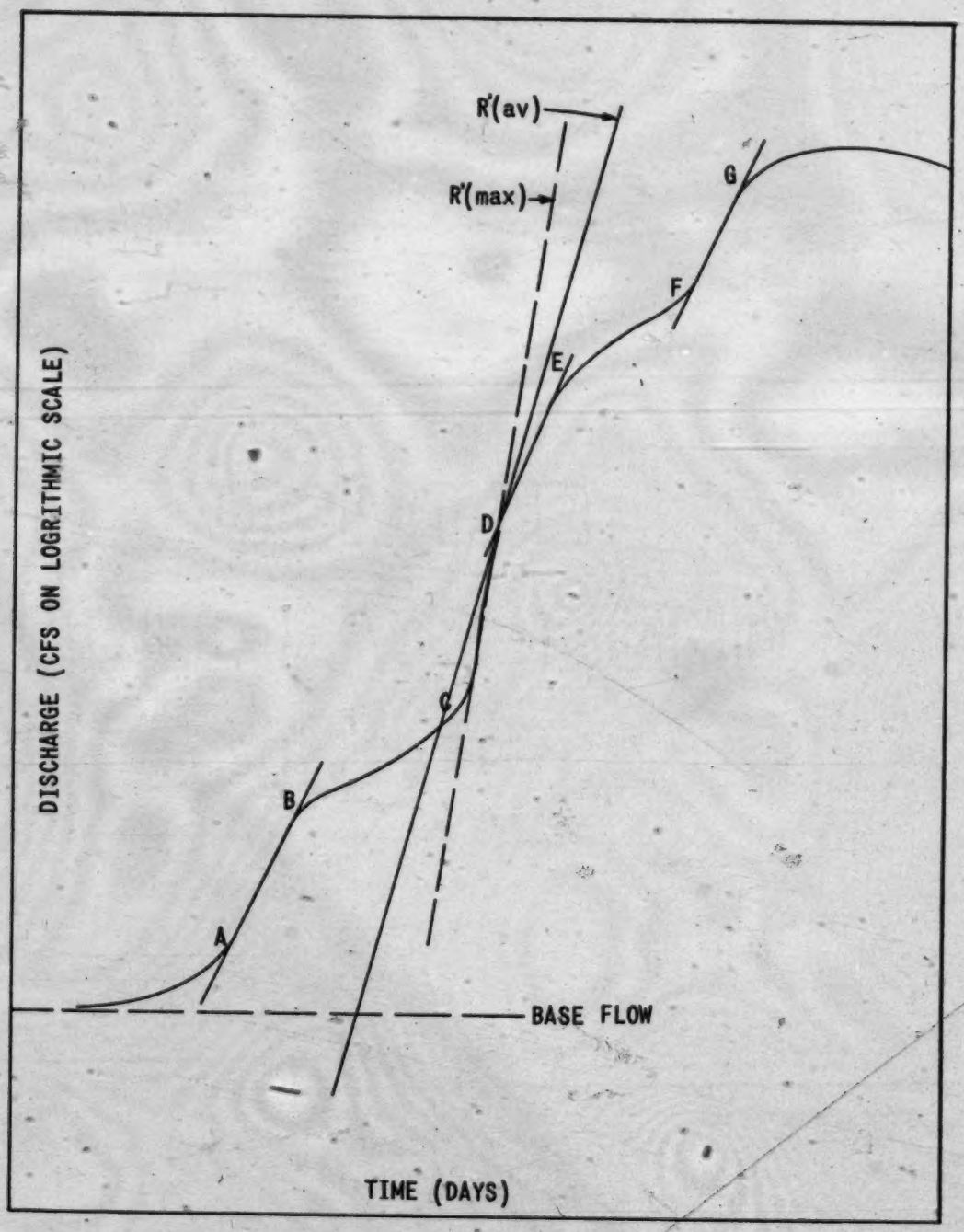


FIG. 3 TYPICAL RISING LIMB OF COMPOSITE HYDROGRAPH SHOWING TWO MEASURES OF ITS STEEPEST SLOPE

For the falling limb, the two slopes K'(max) and K'(av) were selected in a similar manner.

An unexpected feature exhibited by many of the composite hydrographs was an initial, almost horizontal portion of the rising limb followed by an abrupt upward turn to the approximately straight line portion. The recession limb exhibited a similar trend but the change from the general recession slope to the final horizontal section was more gradual. However, the discharge values of the two horizontal portions were usually very close. This feature indicated that there was a real distinction between baseflow and direct runoff. In other words, that without further precipitation input, the discharge from any particular level would decline quite rapidly to an almost constant value which presumably would be base flow. The discharge associated with the change from the horizontal to the steeply sloping section of the graph was used as the final dependent variable in the regression analysis (BF).

For those stations where the minimum recorded discharge was zero (i.e., those rivers that intermittently dry up), there was no transition between zero flow and the straight line portion: the straight line continued at the same slope right down to zero - even steepening on occasions as it approached.

A list of the hydrograph slopes and baseflow values is given in Appendix II, and a description of the regression analyses, with the watershed characteristics as independent variables, is given in Section 4.2.

CHAPTER 3

THEORY OF CORRELATION & REGRESSION

A brief overview of linear regression and correlation is given together with definitions of some of the more important parameters calculated in the following sections: -

3.1 Correlation Between Two Variables

Consider a set of observations on two variables, X and Y, then the simple correlation coefficient (r_{xy}) is defined as the covariance divided by the product of the standard deviations of the two variables ($-1 < r_{xy} < +1$). The simple correlation coefficient is a measure of the linear association between the two variables. If X can be expressed as an exact linear function of Y, then $r_{xy} = \pm 1$. The closer the absolute value of r_{xy}, approaches zero, the further the observations depart from a linear relationship.

Consider now a set of observations on n variables $X_1, X_2 \ldots X_n$. A high simple correlation coefficient (r_{12}) may exist between X_1 and X_2 as defined above, which may be because: -

i) an increase or decrease in X_1 causes an increase in X_2

or

ii) an increase in X_1 and X_2 is caused by an increase in one or more of $X_3 \ldots X_n$.

Thus, r_{12} may give a false impression of the linear association between X_1 and X_2. Therefore, it is of interest to be able to calculate the correlation coefficient between two variables with the effect of one or more other variables removed. Such a correlation coefficient is known as the partial correlation coefficient and is written $r_{12.34\ldots n}$

and measures the linear association between X_1 and X_2 with the effect of variables $X_3 \ldots X_n$ removed. This is an (n-2)nd order coefficient.

3.2 Linear Regression

The subject of linear regression is concerned with the dependence of one variable (the dependent variable) on a linear combination of a set of other variables (the independent variables).

It is assumed that there is a linear relationship of the form

$$Y = B_o + B_1 X_1 + B_2 X_2 + \ldots\ldots + B_p X_p + u$$

between a dependent variable Y and the independent variables $X_1 \ldots X_p$. The parameters B_o, $B_1 \ldots B_p$ are unknown population regression coefficients and u is an unknown random variable, which is a measure of the departure of Y from an exact linear relationship with the p independent variables. Certain assumptions regarding the distribution of the random variable u need to be made in order to apply statistical tests to the various parameters, but they will not be discussed here (K.W. Smillie, 1965).

Consider n sets of observations of the random variables Y, X_1, $X_2 \ldots X_p$ and that b_o, $b_1 \ldots b_p$ are estimates of the population regression coefficients B_o, $B_1 \ldots B_p$.

Then $Y_i = b_o + b_1 X_{i1} + b_2 X_{i2} \ldots b_p X_{ip} + e_i$, Eq. 3.1

where e_i is an estimate of u_i and is called the i^{th} residual. An estimate of Y_i can be made using the regression equation, thus

$$Y_i' = b_o + b_1 X_{i1} + b_2 X_{i2} + \ldots + b_p X_{ip} \qquad \text{Eq. 3.2}$$

It will be seen that the i^{th} residual e_i is the difference between the observed and estimated value of Y_i.

The values of the regression coefficients b_o, $\ldots b_p$ can be determined by minimizing the sum of the squares of residuals, which

involves the solution of a set of simultaneous equations. When the regression coefficients have been determined, values of Y may be estimated via the regression equation and the n residuals computed.

It can be shown that

$$\Sigma (Y_i-\bar{Y})^2 = \Sigma (Y_i' - \bar{Y}')^2 + \Sigma (Y_i-Y_i')^2 \qquad \text{Eq. 3.3}$$

Where Σ = the sum from i = 1 to n

$\bar{Y}$ = the mean of the observed Y_i

Y_i' = the estimated value of Y_i using the regression equation

$\bar{Y}'$ = the mean of the estimated values.

Equation 3.3 shows that the total sum of squares of deviations from the mean of the dependent variable, has two components: -

i) $\Sigma (Y_i' - \bar{Y}')^2$ = total sum of squares of deviation from the mean of the estimated values of Y

and ii) $\Sigma (Y_i - Y_i')^2$ = the sum of squares of deviation of the estimated value from the observed value.

Or the total variation in the dependent variable

= variation due to regression + residual variation

= explained variation + unexplained variation

3.3 Measures of Multiple Linear Correlation

There are several parameters which measure the degree of multiple linear correlation between variables, one of which is the multiple correlation coefficient (R) defined as the simple correlation coefficient between the observed values of the independent variables and the values estimated from the multiple regression function. If the observed and estimated values are equal, then the multiple correlation coefficient will be 1.

It can be shown that

$$R^2 = \frac{\text{explained variation}}{\text{total variation}} = \frac{\Sigma (Y_i' - \bar{Y})^2}{\Sigma (Y_i - \bar{Y})^2} \qquad \text{Eq. 3.4}$$

Another measure of multiple linear correlation is the residual mean square (S^2) which measures the closeness with which the estimated values approach the observed values. To obtain the unbiased estimate of S^2, the residual mean square must be adjusted for the number of degrees of freedom, thus

$$\hat{S}^2 = \frac{1}{n-p-1} \cdot \Sigma (Y_i - Y_i')^2 \qquad \text{Eq. 3.5}$$

where p is the number of independent variables in the regression equation.

A third measure of multiple linear correlation is the <u>standard error of estimate</u> and is defined as the square root of the residual mean square as defined above.

As stated previously, the sample regression coefficients $(b_o, b_1, \ldots b_p)$ are merely estimates of the population coefficients $(B_o, B_1, \ldots B_p)$ and are therefore random variables themselves. It may be shown that any multiple regression coefficient b_j is normally distributed with a mean of B_j and that the unbiased standard error of estimate of b_j is

$$\hat{S}_{b_j} = \frac{S}{s_j} \sqrt{\frac{1}{(n-p-1) \cdot (1-R_j^2)}} \qquad \text{Eq. 3.6}$$

where S = the standard error of estimate (biased)

s_j = the standard deviation of the marginal distribution of variable X_j

and R_j = multiple correlation coefficient of X_j with respect to all other independent variables.

3.4 The "Independent" Variables

From the definition of the multiple correlation coefficient, we know that if the so-called independent variables have no linear association amongst themselves, then $R_j = 0$ and the standard deviation of any regression coefficient b_j will be a minimum (Eq. 3.6). As the degree of linear association amongst the "independent" variables increases, so R_j increases and $\hat{S}_{b_j}$ increases, so that the regression coefficients become less reliable. In other words, multiple linear regression analysis is valid no matter how much the variables are inter-correlated, but significance tests should be continuously applied to the regression coefficients to avoid their standard deviations becoming so large that the coefficients become worthless.

To prevent the likelihood of the above pitfall, the independent variables used may be screened, by calculating a (p x p) matrix of the (p-2)nd order partial correlation coefficients i.e., $r_{12.34....p}$ etc., and eliminating those independent variables which have high partial correlation coefficients, (> 0.5 for example).

The (p-2)nd order partial correlation coefficients may be easily calculated from the formula

$$r_{ij.1,2,..... i-1, i+1, ...j-1, j+1, ...p} = \frac{-{}^*c_{ij}}{\sqrt{{}^*c_{ii} \cdot {}^*c_{jj}}} \qquad \text{Eq. 3.7}$$

where ${}^*c_{ij}$ is the ijth element in the inverse matrix of simple (zero-order) correlation coefficients.

These partial correlation coefficients provide a true measure of the intercorrelation between the independent variables and should be used in preference to the simple correlation coefficients

for selecting variables to include in the analysis.

3.5 Step Wise Multiple Linear Regression

A method exists which introduces the variables into the regression equation one by one, according to their contribution to the reduction of the sum of squares of deviations of the dependent variables. (K.W. Smillie, 1965). This allows significance tests to be applied to the regression coefficients, and a check to be made on the unbiased standard error of the estimate at each step, so that the introduction of new variables can be stopped when the unbiased standard error becomes a minimum or the regression coefficient of the last variable introduced becomes non-significant.

The selection of the variables to be introduced proceeds as follows: -

The squares of the simple correlation coefficients between the dependent and each of the independent variables (r^2_{yj}) are calculated. The first variable to be introduced into the regression equation $Y = b_o^{(1)} + b_1^{(1)} X_j$ is the one with the largest correlation coefficient squared, i.e., the one that explains the largest portion of the variation of the dependent variable, X_A for example.

Now, the squares of the first-order partial correlation coefficients $r_{yj.A,}$ for all $j \neq A$, give the proportion of the variation of Y, unaccounted for by X_A, which may be explained by each of the remaining independent variables. The variable which is introduced next into the regression function is that one, X_B for example, which accounts for the largest portion of the remaining variation. The regression equation then becomes $Y = b_o^{(2)} + b_1^{(2)} X_A + b_2^{(2)} X_B$

Subsequently, variables are introduced into the equation on

the basis of the largest square of the partial correlation coefficient of Y on the independent variables, with the effects of the variables already in the equation (X_A, X_B, etc.) partialled out.

The basic criteria used to determine which variable is introduced into the equation, is that the variable should contribute most to the reduction of "unexplained variation" at each step. This does not imply that successive steps reduce the unexplained variation by decreasing amounts. For example,

Let V_i = portion of variance explained at step i

then for i = 1, $V_1 = r^2_{yA}$

and for i = 2, $V_2 = (1 - r^2_{yA}) \cdot r^2_{yB.A}$

Let $r^2_{yA} = 0.2 > r^2_{yB}$

and let $r^2_{yB.A} = 0.3$

then $V_1 = r^2_{yA} = 0.2$

and $V_2 = (1 - 0.2) \times 0.3 = 0.24$

i.e $V_2 > V_1$

Thus the portion of the "unexplained variation" reduced in the first step is 0.2, and the portion reduced in the second step is 0.24.

If the independent variables are highly correlated amongst themselves, then their rank, on the basis of each successive order of partial correlation coefficients, can change drastically from step to step, as one more variable is partialled out.

It is possible that a variable may rank high according to its (p-2)nd order partial correlation coefficient with Y, but not be introduced into the equation on the basis of its intermediate order partial correlation coefficients. Thus, if R_q is the value of the multiple correlation

coefficient after the introduction into the regression equation of q variables from p independent variables, then it may be possible to introduce a different set of q variables into the equation which will yield a higher value of R_q. (Yevjevich, 1972). This is a further reason to screen the independent variables for intercorrelation, before applying the step-wise multiple regression procedure.

3.6 Confidence Intervals On Estimated Values

If the multiple linear regression equation is used to predict a single value (Y') of the dependent variable for a set of values of the p independent variables, then it can be shown (Brownless, 1960) that the variance of Y' is given by: -

$$\text{Var } (Y') = \sigma^2 \left[\frac{1}{n} + \sum_{i=1}^{p} (x_i - \bar{x}_i)^2 \, c_{ii} + 2 \sum_{i=1}^{p-1} \cdot \sum_{j=i+1}^{p} (x_i - \bar{x}_i) \cdot (x_j - \bar{x}_j) \, c_{ij} \right] \qquad \text{Eq. 3.8}$$

where c_{ij} is the ijth element in the variance-covariance matrix (i.e., the inverse matrix of the normal equation coefficients). σ is the standard deviation of the population random components and can be replaced by $\hat{s}$, the unbiased standard error of the estimate.

This leads to the $100(1 - \alpha)$ confidence intervals: -

$$Y' \pm t_{1-\alpha/2} \, S \sqrt{\text{Var } (Y')} \qquad \text{Eq. 3.9}$$

It can be seen from equations 3.8 and 3.9 that the confidence limits for a particular estimated value of Y' are not unique. A particular value of Y' can result from an infinite number of different combinations of values of the independent variables in the regression equation. Each combination, while yielding the same mean value of Y' will produce different values for the confidence limits.

CHAPTER 4

REGRESSION ANALYSIS

4.1 Watershed Characteristics included in Regression Analysis

The drainage basin characteristics included in the regression analysis follow closely those proposed by Spence (1971) and adopted by Verschuren (1973). The number of parameters included in this study was reduced and the method of determination of others modified as a result of the experience gained in the previous works.

The parameters included met the following requirements: -

i) A strong possibility that each parameter had a direct physical influence on the rate or volume of runoff,

and

ii) Each parameter could be easily and accurately determined from 1:250,000 topographic maps. (The largest scale maps which provide a complete coverage of the entire study area are those at 1:250,000).

A list of characteristics and the abreviations used is given in Table 1.

The topographic drainage area (TDA) is that given by Water Survey of Canada and is the gross drainage area. The study by Spence indicated that the refinement of subtracting areas which are internally draining, to yield the net drainage area, is unwarranted. The area of the watershed has a strong influence on the volume of runoff and on the peak discharge.

The area of lakes (LA) was calculated as a percentage of the drainage basin area, and was included because lakes have a damping effect on a flood wave. The distribution of the lakes throughout the basin also affects damping, but a single factor to measure the distri-

No.	Basin Characteristic	Symbol	Unit
1	Topographic Drainage Area	TDA	sq. mls.
2	Lake Area	LA	% of TDA
3	Forest Area	FA	% of TDA
4	Main Channel Length	MCL	mls.
5	Basin Shape Factor	BSF	
6	Basin Aspect (East/West Component)	BA(X)	
7	Basin Aspect (North/South Component)	BA(Y)	
8	Divide Elevation	DE	ft. above mean sea level
9	Gauge Elevation	GE	ft. above mean sea level
10	Maximum Elevation	ME	ft. above mean sea level
11	Basin Elevation	BE	ft. above mean sea level
12	Basin Relief	RE	ft.
13	Main Channel Slope	MCS	ft./ml.
14	Basin Latitude	LAT	degrees
15	60 min. rainfall: 25 yr. return period	RAIN	ins.

TABLE I DRAINAGE BASIN CHARACTERISTICS

bution is not easy to determine, and not included.

Vegetative cover and land use also affect the volume and rate of runoff in as much as they have a strong influence on infiltration rates and evapotranspiration losses. However, detailed information is not readily available, so the only vegetation parameter included was the area occupied by forests or orchards (FA) expressed as a percentage of drainage area. This information was measured from 1:250,000 scale maps and is consequently imprecise.

The main channel length (MCL) was defined as the distance from the gauging station to the end of the most remote tributary, measured along the river channel. The distance was determined using a map measurer. Meanders too small to be measured with this instrument were ignored. (The limited accuracy with which the MCL could be measured did not warrant the introduction of the closely related parameter basin length advocated by Spence).

The basin shape factor (BSF) was defined as the square of the main channel length divided by the topographic drainage area. It provides an indication of the way in which the basin area is distributed in relation to the main channel, which in turn influences the rate of concentration of runoff at the gauging station from the various basin parts. Using the above definition, two basins with the same areal shape, slope and main valley pattern, will have different values of basin shape factor according to the degree of meandering of the channel within the main valley. This is in agreement with the different hydrograph shapes expected from an identical input over two such basins.

Basin aspect is the predominant orientation of the basin, measured as one of the eight points of the compass. It is introduced

as two parameters to take account of its cyclicity. BA(X) is a measure of the East/West component of basin aspect and BA(Y) is a measure of the North/South component. Both parameters have been assigned arbitrary ranges of 0.0 to +2.0. Basin aspect has an effect upon snowmelt rates, soil moisture conditions and vegetation types, which in turn influence hydrograph shape.

Four parameters which measure watershed elevation are included since elevation has a strong influence on the amount and nature of precipitation incident on an area. Gauge elevation (GE) and maximum elevation (ME) are self-explanatory. The divide elevation (DE) is the elevation of the point where the main channel extended, intersects the watershed boundary.

The elevation of two points were determined; 10% and 85% of the distance along the main channel, measured from the gauging station. The basin elevation (BE) is defined as the mean of these two elevations, and the main channel slope (MCS) is defined as the difference between these two elevations divided by the length of channel between them.

Basin relief (RE) is defined as the difference between the gauge elevation and the maximum elevation.

The foregoing thirteen parameters were initially used as independent variables in the regression analysis. As the analysis progressed, it became apparent that possibly some improvement could be made by the inclusion of further watershed characteristics. The following two parameters were therefore determined: -

i) the latitude of the centre of area of the watershed expressed in degrees, used as a measure of the

geographic location of the basin, (LAT)

ii) the depth of rainfall occurring in one hour which will be equalled or exceeded on average once in 25 years (RAIN). This characteristic is not intended to represent the input which would produce the composite hydrographs described in Section 2, but rather to group and separate basins into different climatic regions.

The fifteen drainage basin characteristics described above were determined for each watershed and are listed in Appendix III.

4.2 Regression Analysis and Results

An attempt was made to determine the best linear relationship between each of the dependent variables (R(av), R(max), K(av), K(max) and BF) and the selected independent variables, using a stepwise linear regression program (STPRG step-wise regression). Basically, the program operates as follows: -

In the first step, the regression equation is found between the dependent and one independent variable; in each subsequent step one variable is added and the new regression equation determined. (For fuller explanation, see Section 3.5). The multiple correlation coefficient is determined at each step together with its unbiased standard error of estimate, the regression equation coefficients and their corresponding standard errors of estimate. In general, independent variables are introduced into the analysis until the unbiased standard error of the estimate reaches a minimum value. However, if the correlation between the dependent variable and the last independent variable is weak, then the associated regression coefficient may be statistically

insignificant, in which case, the last step should be deleted and the analysis terminated. This will result in a legitimate value of the multiple correlation coefficient somewhat lower than the value obtained in the final step.

The technique is purely an arithmetic one and does not assess whether the relationship given by the regression equation is physically realistic.

In order to obtain the highest significant value of the multiple correlation coefficient (i.e., the best linear relationship), several separate runs using program SSPLIB were carried out for each of the five dependent variables (R(av), R(max), K(av), K(max) and BF). To illustrate this sequence, the following is a brief description of each run using the average rate of rise R(av) as the dependent variable. A complete list of regression equations for R(av) is given in Table 2.

The first run included data from all 62 stations which met the requirements of Section 1.4. The first 13 variables of Appendix III, i.e., those discussed in Section 4.1, were made available for inclusion into the regression equation, step by step.

Significance tests indicated that the first four regression coefficients only were significant at the 5% level. The resulting equation is Equation 4.1 and the corresponding value of the multiple correlation coefficient (R) is 0.65.

For the second run, common logarithms were taken of all the variables, and again, all the independent variables were available for selection. It can be seen from Table 2 that the multiple correlation coefficient increased to 0.71. To enable logarithms to be taken, all the independent variables were screened and any zero values were

Run No.	Description of Variables Included	Regression Equation	Multiple Correlation Coefficient	Eqn. No.
1	Basic 62 Stations 13 independent vars. included Arithmetic vars.	$R(av)=.29+.001(TDA)+.0001(RE)$ $-.0001(DE)-.0008(MCL)$	0.65	4.1
2	Basic 62 Stations 13 independent vars. included Log_e of variables	$R(av)=.0088x(TDA)^{.39}x(FA)^{.22}$ $x(BSF)^{-.49}x(RE)^{.30}$	0.71	4.2
3	Basic 62 Stations 13 independent vars. included Variables raised to powers	$R(av)=-.62+.0003(TDA)^{.56}$ $-.05(BSF)^{1.0}+.003(RE)^{0.55}$ $+.92(MCS)^{-0.2}+0.28(FA)^{0.37}$	0.74	4.3
4	Basic 62 Stations 8 "reasonable" indep. vars. Arithmetic vars.	$R(av)=0.18+.000009(TDA)+.000041(RE)$ $-.013(BSF)-.0067(MCS)+.0016(FA)$	0.69	4.4
5	Basic 62 Stations 8 "reasonable" indep. vars. Log_e of vars.	$R(av)=.0088x(TDA)^{.39}x(FA)^{.22}x(BSF)$ $-.49x(RE)^{.30}$	0.71	4.5
6	Basic 62 Stations 7 indep. vars.-best zero order correlation coeffs. Arithmetic vars.	$R(av)=0.10+0.00(TDA)-.0073(BSF)$ $+0.00(ME)-0.07.BA(X)-.007(LA)$	0.64	4.6

TABLE 2 RESULTS OF STEPWISE LINEAR REGRESSION ANALYSIS WITH R (av) AS DEPENDENT VARIABLE

Run No.	Description of Variables Included	Regression Equation	Multiple Correlation Coefficient	Eqn. No.
7	Basic 62 Stations 8 indep. vars.-best partial correlation coeffs. Arithmetic vars.	$R(av) = 0.31 + .000026(TDA) - .00092(MCL) + .000063(ME) - .0003(BE) + 00017(GE) + .0013(RE)$	0.72	4.7
8	Basic 62 Stations Log_e of variables 8 indep. vars.-best partial correl. coeffs.of logs of vars.	$R(av) = .000023 x(TDA)^{.26} x(FA)^{.24} x(BSF)^{-0.5} x(ME)^{.92} x(MCS)^{.41}$	0.74	4.8
9	Basic 62 Stations 7 indep. vars.-best partial correl. coeffs. indep. vars. raised to powers	$R(av) = -0.5 + 0.0024(TDA)^{.56} - 0.07(MCL)^{.42} + .004(RE)^{.55} + 0.99(MCS)^{-0.2} + 0.29(FA)^{.37}$	0.75	4.9
10	Basic 62 Stations 7 indep. vars.-best partial correl. coeffs. indep. vars. raised to powers	$R(av) = -0.29 + 0.74(MCS)^{-.20} + .08(RAIN)^{-1.46} + .003(RE)^{.55} - .056(MCL)^{.42} + .002(TDA)^{.56}$	0.76	4.10
11	Lake Stations deleted 7 indep. vars.-best partial correl. coeffs. indep. vars. raised to powers	$R(av) = -.48 + .026(RAIN)^{-1.46} + 0010(TDA)^{.60} + .025(FA)^{.35} - .0081(MCL)^{.64} + .0036(RE)^{.50} + .063(MCS)^{.22}$	0.80	4.11

Note: Run Nos. 10 & 11 were made with Drainage Basin characteristics LAT and RAIN available for selection.

TABLE 2 (CONT) RESULTS OF STEPWISE LINEAR REGRESSION ANALYSIS WITH R (av) AS DEPENDENT VARIABLE

arbitrarily set to 0.1. This was well within the accuracy with which the variables had been determined.

Prior to making the third run, thirteen separate runs were made using logarithms of variables, each run having one independent variable available for selection. This resulted in thirteen separate equations of the form: -

$$R(av) = A_n \times X_n^{B_n}$$

with $n = 1,2...13$,

X_n representing the independent variables,

and A and B - constants.

For the third run, the independent variables were raised to the respective B_n powers. The result is Eq. 4.3 and the value of the multiple correlation coefficient is 0.74.

In an attempt to obtain a regression equation which was physically realistic, the number of independent variables available for selection in the fourth run was restricted to eight. They were the ones thought most likely to affect hydrograph shape and which had, in addition, relatively low zero-order correlation coefficients between themselves ($|r_{ij}| < 0.44$). The variables available for selection were:-

1. Topographic Drainage Area (TDA)
2. Lake Area (LA)
3. Forest Area (FA)
4. Basin Shape Factor (BSF)
5. Basin Aspect (X direction) (BA(X))
6. Basin Aspect (Y direction) (BA(Y))
7. Basin Relief (RE)
8. Main Channel Slope (MCS)

the regression equation resulting from this run is:

$$R(av) = 0.18 + .000009\,(TDA) + .00004(RE) - .013(BSF) - .0067(MCS) + .0016(FA) \qquad \text{Eq. 4.4}$$

with multiple correlation coefficient of 0.69. Noting that a large value of rate or rise R(av) indicates a flat slope for the rising limb of the hydrograph and that basin shape factor is defined as main channel length divided by topographic drainage area, it can be seen that the sign of the coefficients of TDA, MCS and FA appear physically realistic, but those of RE and BSF do not.

The fifth run was similar to that just described except that logarithms of variables were used. The multiple correlation coefficient increased slightly to 0.71, MCS was not introduced into the equation, and the sign of the coefficients of BSF and RE remained "wrong". Thereafter, attempts to keep the equation physically realistic were abandoned.

It appeared from the results of the first five runs that at most, six independent variables contributed significantly to the reduction in variation of the dependent variable, so for the next run, the seven independent variables which had the lowest zero-order correlation coefficients between themselves were included. A low value of the multiple correlation coefficient of 0.64 resulted.

It was apparent that zero-order correlation coefficients did not give a true indication of the correlation between variables. Therefore, a small program was written to calculate the matrix of twelfth order partial correlation coefficients (see Section 3.1) which gave a measure of the true correlation between two variables with the effects of all other variables removed.

The seventh run was made with eight independent variables

available for selection. The selected variables had high twelfth order partial correlation coefficients with the dependent variable and were not highly correlated to each other. Five variables which did not meet these criteria were eliminated. The run was made with arithmetic variables, and a multiple correlation coefficient value of 0.72 resulted.

For the next run, common logarithms were taken of the variables and the twelfth order partial correlation matrix calculated. From this, the eight variables were selected for inclusion using the same criteria as for the previous run. The multiple correlation coefficient increased to 0.74. Three variables from the previous equation also appeared in this result.

The ninth run was made using seven independent variables raised to powers (as discussed for run No. 3). The seven variables included were selected from a new matrix of twelfth order partial correlation coefficients using the same criteria as before. The multiple correlation coefficient reached a high of 0.75.

It can be seen from Table 2 that TDA was the first variable to be included in the regression equation for each of the nine runs. This is so because, of the particular set of independent variables included in each run, the relevant function of TDA had the highest zero order correlation coefficient with the dependent variable (see Section 3.5).

The regression equation resulting from the ninth run was the best that had so far occurred, in as much as the multiple correlation coefficient was the highest, and it appeared that little improvement could be made using the independent variables already available. Consequently, a plot was made of observed (i.e., obtained from the composite

hydrographs) values of R(av) versus values calculated using Equation 4.9. There was considerable scatter about a line bisecting the axes and passing through the origin. In order to see if any pattern existed, the 62 stations were divided into five groups on the basis of their geographic location, vis: foothills, prairies, aspen parkland, boreal forest, Yukon and N.W.T. A symbol was selected to represent each group and the symbol appropriate to each station location was marked adjacent to the points on the plot. It was apparent that the values calculated using the regression equation were too high for those stations in the prairies, aspen parkland and foothills, and to a lesser extent, too low for those stations in the boreal forest. The northern stations were widely scattered.

In order to improve the regression equation, a parameter or parameters, were required that would connect the stations of the prairies, aspen parkland and foothills, and distinguish them from the stations of the boreal forest. Station latitude was chosen for this purpose, although it was appreciated that the foothills spanned a considerable latitude range, and that the scatter of the Yukon and N.W.T. stations on the plot would not be reduced since the station latitude values would all fall within a narrow band. In addition, it was realized that latitude probably had no direct effect on hydrograph shape, but that some topographical or climatological condition may be associated with latitude, which would have an influence.

A parameter which more clearly divided the stations in the desired manner was found to be the 60 minute rainfall depth having a return period of 25 years. The inclusion of this parameter is justified because the hydrograph parameters being considered are for runoff events

of low probability and therefore 25 years return period rainfall could be relevant. Also, many of the isohyetal maps for different durations and return periods had similar general shapes and therefore the choice was not critical.

The values of the two additional independent variables (LAT and RAIN) are given in Appendix III for each station.

The tenth run was made using variables raised to powers. Using all fifteen independent variables, the matrix of fourteenth order partial correlation coefficients was determined. Station latitude was not well correlated with the dependent variable and was not included amongst the seven independent variables available in the regression analysis. The resulting equation (Eq. 4.10 Table 2) has the main channel slope as the first variable, the new rainfall parameter (RAIN) next and the drainage area last. The multiple correlation coefficient of 0.76 is a slight improvement over the previous highest.

Another plot was made of "observed" versus calculated values of R(av) using the new equation. A slight readjustment of the grouping of the stations occurred but there was still considerable scatter.

It was noticed that the two stations which had the greatest difference between "observed" and calculated values (Stations 32 and 42) were at or near the outlet of large lakes. Three other stations (44, 45 and 46) were found to be similarly situated, and in each case the "observed" value of R(av) was considerably greater than the calculated value. This is due to the reduction of the flood peak as it is routed through the lake, which results in a flatter hydrograph and consequently higher values of R(av). It was considered that the stations close to lake outlets belonged to a different population, and therefore it was legiti-

mate to exclude these stations from the analysis.

The final run in this series, run eleven was made using only the data from the 57 non-lake-outlet stations. The independent variables were raised to powers as in the previous run. The resulting equation is:-

$$R(av) = -.48 + .026(RAIN)^{-1.46} + .001(TDA)^{.60} + .025(FA)^{.35} - .0081(MCL)^{.64} + .0036(RE)^{.50} + .063(MCS)^{-.22} \qquad \text{Eq. 4.11}$$

and the multiple correlation coefficient is 0.80; the best value obtained.

Initially, runs were made with R(av), R(max), K(av) and K(max) as dependent variables. However, it became apparent that the values of the multiple correlation coefficients, associated with R(av) and R(max) were very similar for each run. The same applied to K(av) and K(max). In order to avoid duplication, R(max) and K(max) were eliminated from the analysis.

An analysis similar to that described above was carried out for the two independent variables; average rate of fall K(av) and baseflow BF. In general, at each stage of the analysis, the multiple correlation coefficient associated with the K(av) equation was somewhat less than that corresponding to R(av), while that associated with BF was somewhat greater. The final equations are given in Table 3.

It is noteworthy that the rainfall parameter (RAIN) and drainage area (TDA) occur in the final equations for R(av), K(av) and BF, and that basin relief (RE) occurs in BF and R(av).

4.3 Map Coefficients

In order to make equations 4.11, 4.12 and 4.13 useful for predictive purposes, maps were prepared showing lines of equal values

Dependent Variable	Description of Variables Included	Regression Equation	Multiple Correlation Coefficient	Eq. No.
K(av)	Lake Stns. deleted 7 indep. variables best partial correlation coeffs. incl. vars. raised to powers.	$K(av) = -0.031 + 0.33(RAIN)^{-.70} + 0.021(TDA)^{0.26}$	0.72	4.12
BF	Basic 62 Stn. Log_e of variables. 8 indep. variables best partial correlation coeffs. of logs of variables.	$\ln BF = -20 - 2.96 \times \ln RAIN - 1.71 \times \ln RE + 1.13 \times \ln TDA$ or $BF^{-1} = 2.99 \times RAIN^{2.96} \times RE^{1.71} \times TDA^{-1.13}$	0.86	4.13

TABLE 3 FINAL RESULTS OF REGRESSION ANALYSIS WITH K (av) AND BF AS DEPENDENT VARIABLES

of the regression coefficient b_o, or intercept. The method is similar for each parameter so the case of R(av) only will be discussed.

Consider a location on an ungauged river within the geographic region of the sample stations, and with a drainage area between 500 and 15,000 square miles. Given Equation 4.11 and the values of the five parameters contained in it (determined from meteorological and topographical maps), the value of R(av) can be determined for the ungauged station. However, the result is not very reliable due to the only moderate value of the multiple correlation coefficient (0.80). The value of R(av) can be improved by using a map coefficient (c) in place of the intercept (b_o). The map coefficient is an amended value of b_o. The amendment is made to account for the effect of parameters not included in the analysis, e.g., soil properties, ratio of rainfall to snowfall, etc. A map showing lines of equal values of c is prepared as follows: -

On an outline map of the geographic region of the sample stations, the station number is marked at the centre of its drainage basin. (The hydrograph parameters reflect the characteristics of the entire basin and not just those of the gauging site). Using Equation 4.11, the values of R(av) are calculated for each station, using the previously determined parameters, and subtracted from the "observed" R(av) values of Appendix II. This difference is then added to the respective b_o value to produce the map coefficient c, which is then marked on the map adjacent to the station number. Lines of equal c values are then drawn, based on the values at each station. A c value for any ungauged station can then be read from the map and substituted for b_o in the regression equation. Maps of Alberta and Yukon Territory

showing map coefficients for R(av), K(av) and BF are given in Appendix IV. If the contours could be drawn exactly as dictated by the spot values, then the calculated values of R(av) for the sample stations would equal the "observed" values. However, in order to obtain reasonably smooth contours some deviation from the calculated c values is necessary which accounts for the scatter on the plots of observed versus calculated values of R(av), K(av) and BF (Figs. 4, 5 and 6).

4.4 Regional Analysis

For this part of the study, the 42 Alberta sample stations were sub-divided on a geographical basis into 4 groups - prairies, foothills, aspen parkland and boreal forest (See Appendix III). This resulted in groups of 8, 12, 7 and 15 stations respectively. Stepwise-multiple linear-regression analyses were carried out on certain groups and combinations of groups in turn, with R(av) as the dependent variable and the 15 independent variables shown in Table 1 available for selection into the regression equation. The results are given in Table 4. While the multiple correlation coefficient of 0.98 obtained for the prairie stations appears very high, it must be remembered that the sample consisted of only eight data points. Similarly, the foothills samples contained only 12 stations.

It would be unwise to use the regression equations for predictive purposes because the confidence bands are very broad due to the small sample size. However, the indications are that, if a large sample from one small geographic region could be obtained, then good correlations might be established.

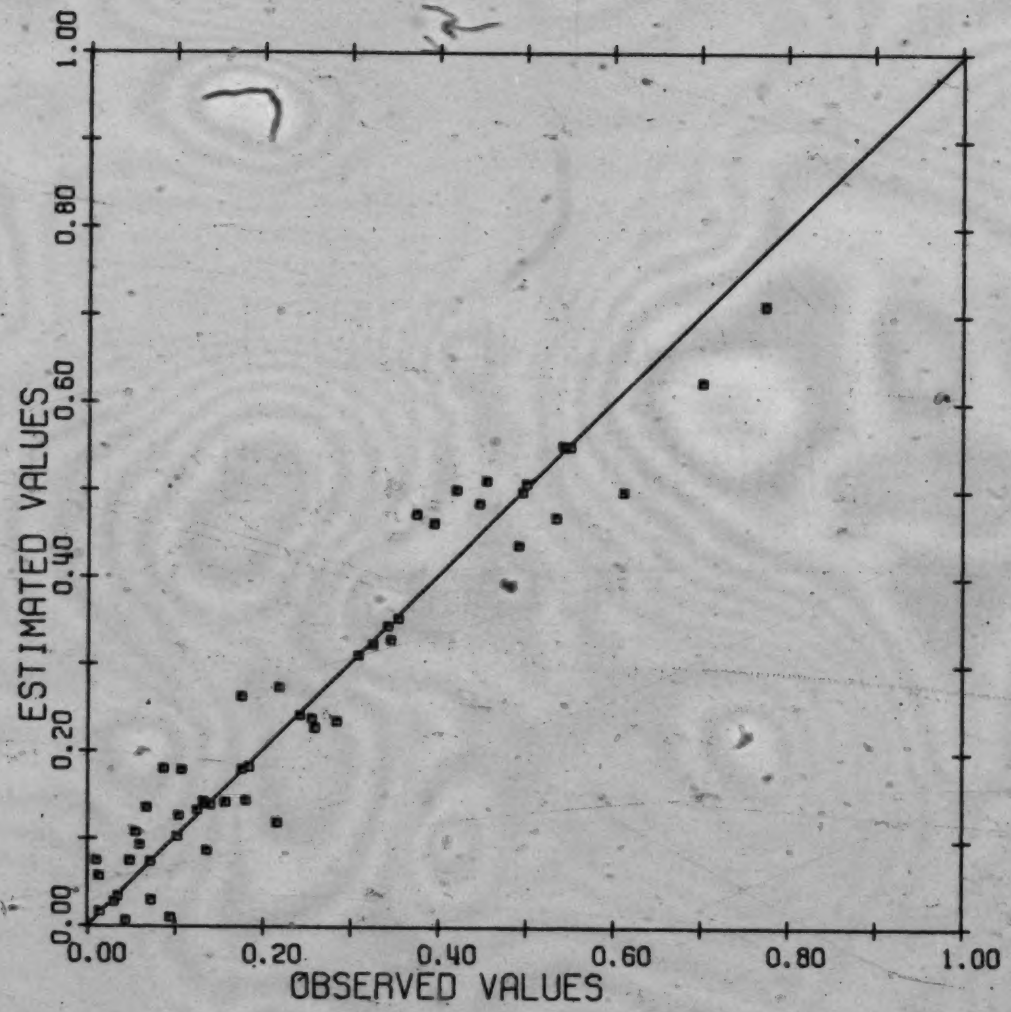


FIG. 4 R (AV): OBSERVED VS. ESTIMATED VALUES BY REGRESSION

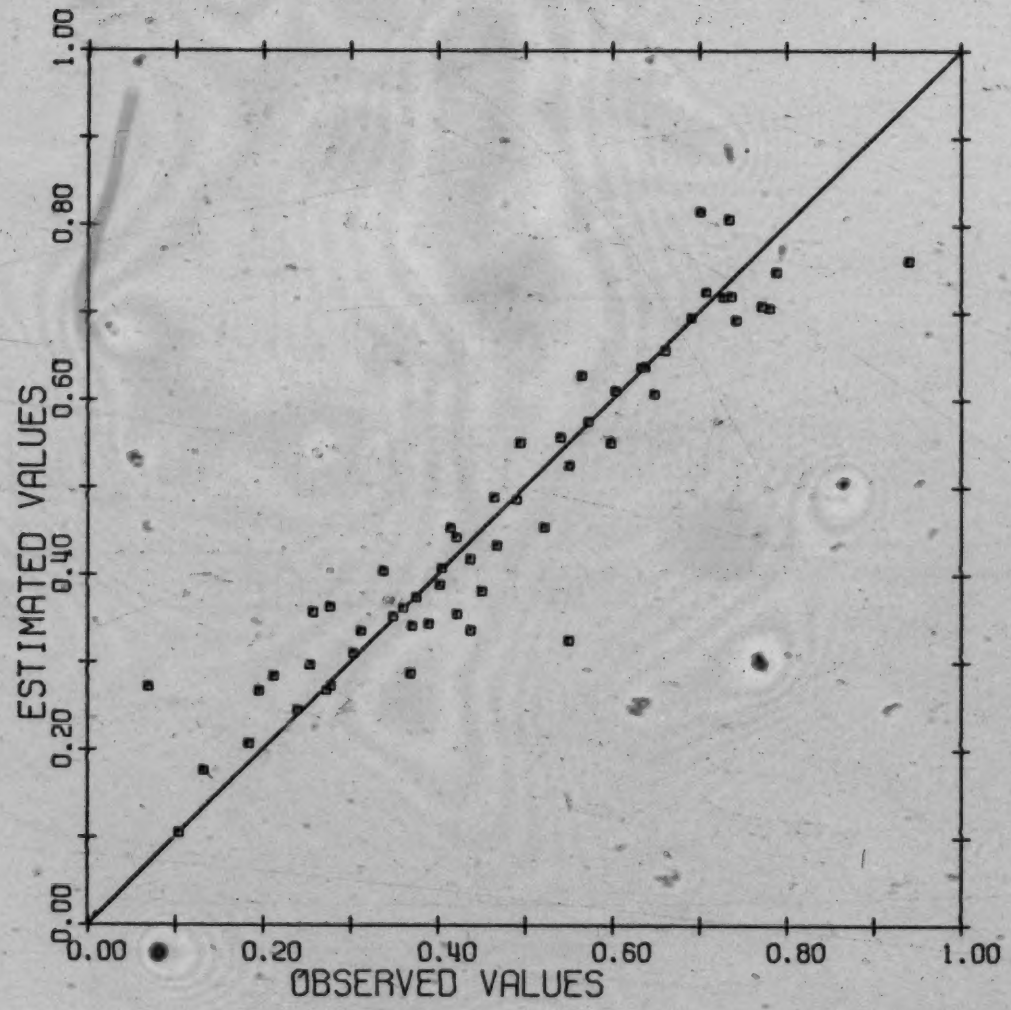


FIG. 5 K (AV): OBSERVED VS. ESTIMATED VALUES BY REGRESSION

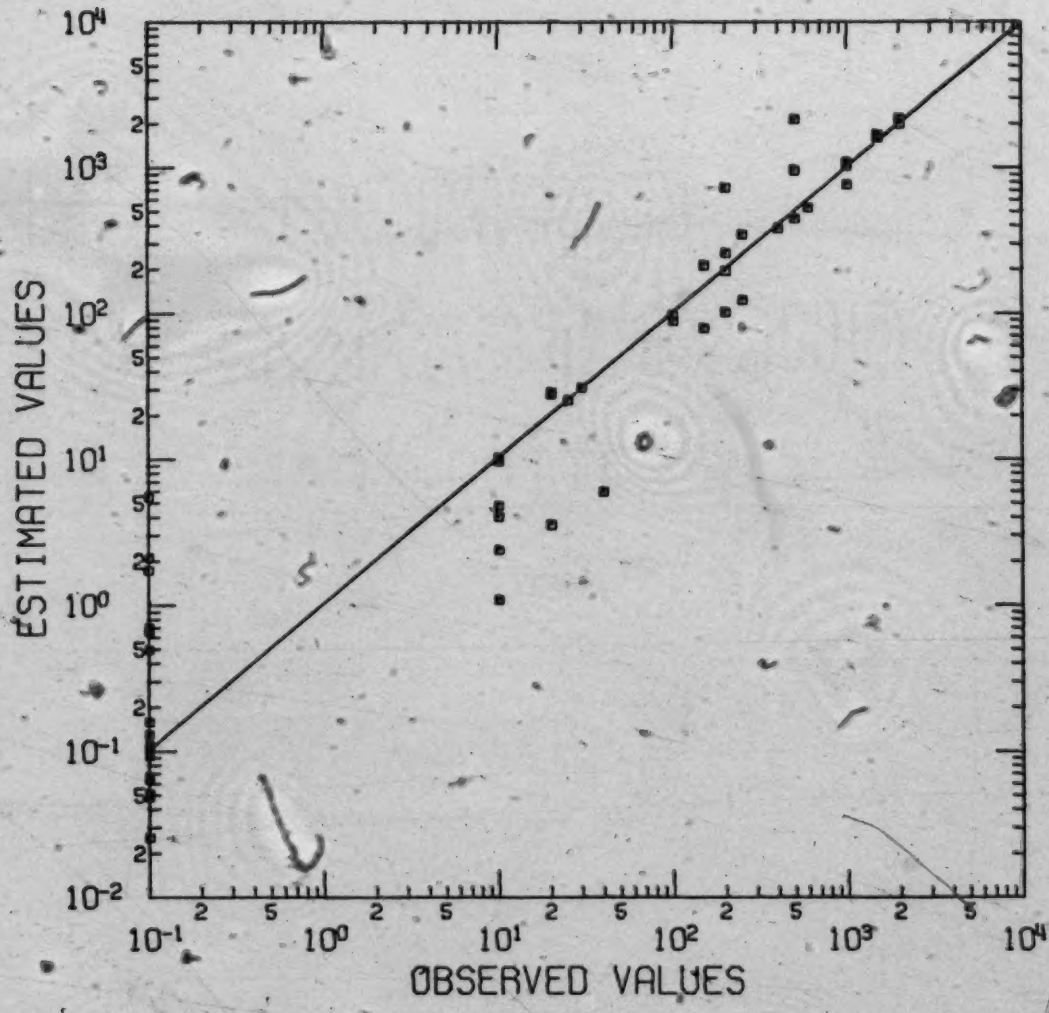


FIG. 6 B/FLW: OBSERVED VS. ESTIMATED VALUES BY REGRESSION

Region	Sample Size	Regression Equation	Multiple Correlation Coefficient
Prairies	8	R(av)=-0.30+.00015(BE)-0.011(LA) -0.000075(TDA)+0.0028(FA)	0.98
Foothills	12	R(av)=1.39-1.32(RAIN)+0.000070(RE) -0.000086(TDA)+0.0027(MCL)	0.91
Prairies + Foothills	20	R(av)=0.21-0.099(BA(Y))+0.000018(BE)	0.53
Prairies + Aspen Parkland	15	R(av)=-0.43+0.22(BA(X))+0.000045(BE) -.0020(BSF)	0.59
Aspen Parkland + Boreal Forest	22	R(av)=0.16+0.000025(TDA)-0.15(BA(Y)) +0.0020(FA)	0.70

TABLE 4 MULTIPLE LINEAR REGRESSION ANALYSIS FOR R (av) FOR ALBERTA STATIONS BY REGIONS

CHAPTER 5

PEAK DISCHARGE

5.1 Theory

It was demonstrated in Section 2.4 that the composite hydrographs, produced by combining the steepest portions of recorded floods hydrographs, when ploted as log Q versus time, resulted in straight lines over considerable discharge ranges. In addition, there often appeared a quite distinct, almost horizontal portion, in the lowest discharge range which has been called baseflow.

Consider the idealized hydrograph of Fig. 7. Fig. 7(a) has an arithmetic time scale and logarithmic discharge scale. Let the rising and falling limbs be straight lines and terminate at a constant discharge value Q_1. Let the peak discharge Q_o occur at t=0. Fig. 7(b) shows the same hydrograph drawn to an arithmetic scale on both axes.

Consider the general equation of a straight line on semi-logarithmic axes.

$$\log Q = m.t + c \qquad \text{Eq. 5.1}$$

where Q and t are the variables

c is the intercept

and m is the gradient

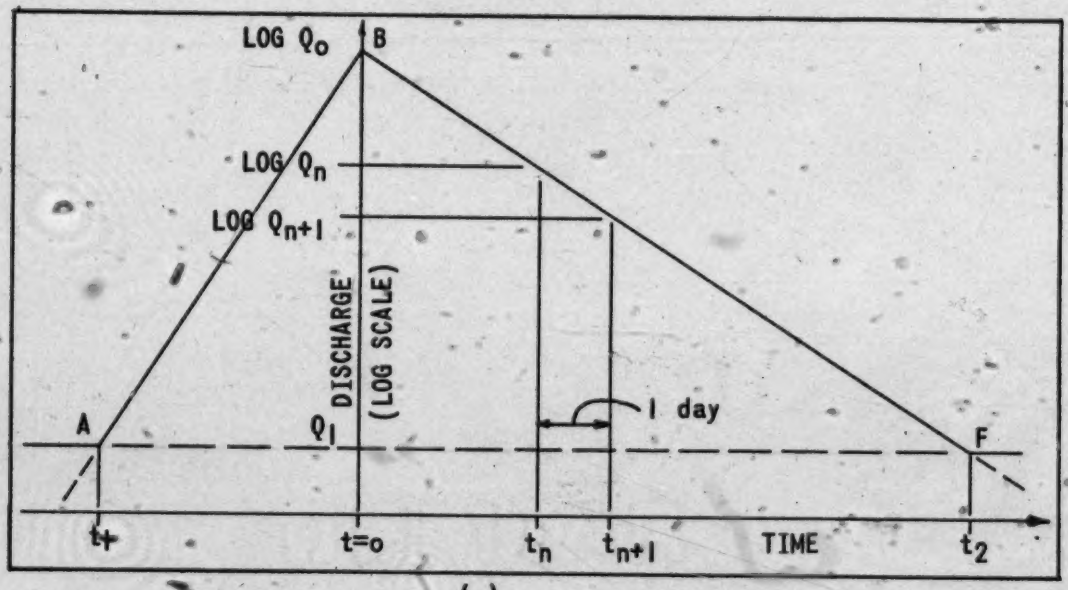
Referring to Fig. 7(a),

$$c = \log Q_o$$

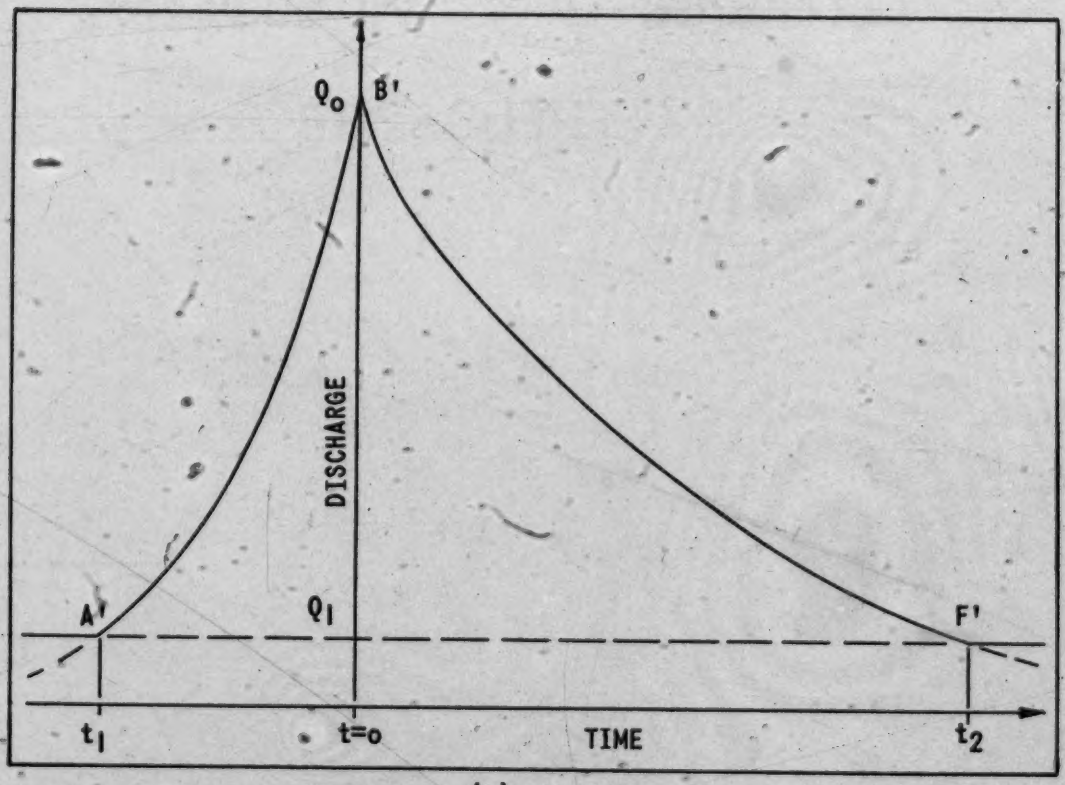
$$\text{and } m = \frac{-(\log Q_n - \log Q_{n+1})}{t_{n+1} - t_n}$$

Substituting for m in Eq. 5.1 gives

$$\log Q = t(\log Q_{n+1} - \log Q_n) + \log Q_o$$



(a)



(b)

FIG. 7 IDEALISED HYDROGRAPH SHAPE

or $$Q = Q_o \left[\frac{Q_{n+1}}{Q_n} \right]^t \qquad \text{Eq. 5.2}$$

For the falling limb of a hydrograph, i.e., negative gradient, define $\frac{Q_{n+1}}{Q_n} = K$ = rate of drop of discharge = $-\frac{1}{K'}$

then $$Q = Q_o (K)^t \qquad \text{Eq. 5.3}$$

For the rising limb of a hydrograph, i.e., positive gradient, define $\frac{Q_n}{Q_{n+1}} = R$ = rate of rise of discharge = $\frac{1}{R'}$

then $$Q = Q_o (R)^{-t} \qquad \text{Eq. 5.4}$$

As defined above, K is the ratio of the discharge on a particular day to the discharge on the previous day. R is the ratio of discharge on a particular day to the discharge on the following day. The range of possible values of R and K is 0.0 to 1.0.

The area under a hydrograph in a particular time interval, represents the volume of runoff in that time. The volume of direct runoff is obtained by subtracting the baseflow volume from the total volume. Referring to Fig. 7 (b), the area A'B'F' represents the volume of <u>direct</u> runoff in the time interval $t_2 - t_1$.

In order to obtain an expression for the volume of direct runoff, consider first the volume of direct runoff during the rising period of the hydrograph.

The volume of direct runoff in the time interval $t = t_1$ to $t = 0$ is equal to the area under the rising limb of the hydrograph and bounded by the line $Q = Q_1$.

The rising limb equation is $Q = Q_o.(R)^{-t}$

$$\text{i.e., } \ln Q = \ln Q_o - t.\ln R$$

$$\text{i.e., } \quad t = \frac{\ln Q_o}{\ln R} - \frac{\ln Q}{\ln R}$$

The volume of direct runoff is given by

$$V_{(t_1-0)} = -\int t.dQ$$

$$= -\int_{Q_1}^{Q_o} \frac{\ln Q_o}{\ln R} \cdot dQ + \int_{Q_1}^{Q_o} \frac{\ln Q}{\ln R} \cdot dQ$$

$$= -\left[\frac{Q.\ln Q_o}{\ln R}\right]_{Q_1}^{Q_o} + \left[\frac{Q.\ln Q - Q}{\ln R}\right]_{Q_1}^{Q_o}$$

which leads to

$$V_{(t_1-0)} = \frac{1}{\ln R}\left[Q_1 (\ln Q_o - \ln Q_1) + Q_1 - Q_o\right]$$

Similarly, the volume of direct runoff during the recession period, i.e., in the time interval $t = 0$ to $t = t_2$ is given by

$$V_{(0-t_2)} = \frac{1}{\ln K}\left[Q_1 (\ln Q_o - \ln Q_1) + Q_1 - Q_o\right]$$

Thus, the total volume of direct runoff

$$V = V_{(t_1-0)} + V_{(0-t_2)}$$

$$\text{i.e., } V = \left[Q_1 (\ln Q_o - \ln Q_1) + Q_1 - Q_o\right]\left[\frac{1}{\ln K} + \frac{1}{\ln R}\right] \qquad \text{Eq. 5.5}$$

The direct runoff volume V can be calculated for a watershed in terms of an average depth of exess precipitation per unit area (d) and the drainage basin area (TDA)

$$\text{i.e., } V = d.(TDA) \qquad \text{Eq. 5.6}$$

Combining Equations 5.5 and 5.6, and rearranging

$$Q_1.\ln Q_o - Q_o = d.(TDA).\frac{(\ln R \times \ln K)}{(\ln R + \ln K)} + Q_1.(\ln Q_1 - 1) \qquad \text{Eq. 5.7}$$

The above is a non-linear equation expressing the peak discharge Q_o in terms of the average depth of excess precipitation, basin area, the rates of rise and fall of the hydrograph and the value of baseflow discharge Q_1.

5.2 Regression Analysis with Peak Flow as the Dependent Variable

For each of the 57 non-lake-outlet study watersheds, a value of peak flow was calculated using Eq. 5.7, for an average depth of excess precipitation from the basin of 1 ins. (Q_o (1")). It should be noted that the volume of runoff, i.e., d x TDA must be expressed in units of cfs. days, i.e., V [cfs. days] = 26.8 x d x TDA where d [ins.] and TDA [sq. mls.]

Q_o (1") calculated using Eq. 5.7 is referred to hereafter as the 'observed' value of peak flow for 1 ins. of excess precipitation. It should not be confused with the actual recorded peak flow of the composite hydrograph. It is a calculated discharge value based on the observed steepest rising and falling limbs of the composite hydrograph.

Q_o (1") was used as the dependent variable in a stepwise regression analysis, with the basin characteristics of Appendix III as independent variables.

The equation which gave the highest value of the multiple correlation coefficient (R=0.88) is: -

$$Q_o(1") = 44.0 \times (TDA)^{0.85} \times BA(Y)^{0.2} \times (RAIN)^{0.63} \qquad \text{Eq. 5.8}$$

The author analyzed hydrographs based on three years of record, from 8 small (less than 165 sq. mls.) watersheds in the vicinity of Watson Lake, Y.T. (Verschuren and Bristol 1974). The hydrographs were based on instantaneous discharges and were analyzed manually to determine the maximum rates of rise and fall. No account was taken of base flow in the study, but it is known that winter flows are extremely small and the effect of the omission is probably negligible.

Peak discharge resulting from 1" of excess precipitation was calculated for the 8 small basins and plotted against basin area, on logarithmic graph paper. The equation of the resulting straight line envelope was found to be:

$$Q_o(1") = 48(TDA)^{.72} \qquad \text{Eq. 5.9}$$

The similarity between this equation and Equation 5.8, derived for much larger basins, is noteworthy.

To enlarge the range and size of the sample, the drainage basin characteristics of these 8 small basins were calculated (Station Nos. 63 - 70 of Appendix III) and another regression analysis was carried out on the sample of 65 stations (lake outlet stations once again being omitted). The results of the analyses for various depths of excess precipitation are given in Table 5, together with values of the multiple correlation coefficients.

Table 6 gives the regression equations obtained at the first step of the stepwise analysis. It will be noted that topographic drainage area is the parameter included and that for depths of excess precipitation of one inch or greater, it occurs raised to the power of 0.88. In addition , it should be noted that the multiple correlation coefficients are at most 0.03 less than the values obtained in Table 5.

Depth of Excess Precip.	Regression Equation	Multiple Correlation Coefficient	Equation No.
0.1 Ins.	$Q_o(0.1") = 2.17 x (TDA)^{0.92} x (RAIN)^{0.53} x (BA(Y))^{0.13}$	0.97	5.10
0.5 Ins.	$Q_o(0.5") = 15.2 x (TDA)^{0.89} x (RAIN)^{0.71} x (BA(Y))^{0.17}$	0.97	5.11
1.0 Ins.	$Q_o(1.0") = 31.4 x (TDA)^{0.88} x (RAIN)^{0.75} x (BA(Y))^{0.18}$	0.97	5.12
2.0 Ins.	$Q_o(2.0") = 64.2 x (TDA)^{0.88} x (RAIN)^{0.77} x (BA(Y))^{0.19}$	0.97	5.13
5.0 Ins.	$Q_o(5.0") = 162.9 x (TDA)^{0.88} x (RAIN)^{0.97} x (BA(Y))^{0.19}$	0.97	5.14
10.0 Ins.	$Q_o(10.0") = 328.2 x (TDA)^{0.88} x (RAIN)^{.80} x (BA(Y))^{0.19}$	0.96	5.15

TABLE 5 REGRESSION EQUATIONS OF PEAK DISCHARGE FOR VARIOUS DEPTHS OF EXCESS PRECIPITATION

Depth of Excess Precip.	Regression Equation	Multiple Correlation Coefficient	Equation No.
0.1 Ins.	$Q_o(0.1") = 2.58x(TDA)^{0.92}$	0.96	5.16
0.5 Ins.	$Q_o(0.5") = 14.4x(TDA)^{0.89}$	0.95	5.17
1.0 Ins.	$Q_o(1.0") = 29.4x(TDA)^{0.88}$	0.95	5.18
2.0 Ins.	$Q_o(2.0") = 60.3x(TDA)^{0.88}$	0.94	5.19
5.0 Ins.	$Q_o(5.0") = 152.5x(TDA)^{0.88}$	0.94	5.20
10.0 Ins.	$Q_o(10.0") = 307.2x(TDA)^{0.88}$	0.94	5.21

TABLE 6 REGRESSION EQUATIONS FOR PEAK FLOW VS. TOPOGRAPHIC DRAINAGE AREA

Fig. 8 shows plots of the intercept of the regression equation versus depth of excess precipitation for the equations of Tables 5 and 6. It can be seen that the intercept increases virtually linearly with excess precipitation.

Fig. 9 shows a plot of 'observed' $Q_o(1")$ values (i.e., calculated using Eq. 5.7) versus values calculated using the regression equation given in Table 5 (Eq. 5.12). Because logarithms of variables were used in the regression analysis, there is considerable scatter of the points in spite of the high multiple correlation coefficient of 0.97. In order to make the regression equation more useful for peak flow prediction, map coefficients have been determined (Appendix IV). In order to utilize one set of map coefficients for the six regression equations derived for the six depths of excess precipitation shown in Table 5, the 'contour' values for Q_o shown in Appendix IV are factors by which the regression equations are to be multiplied (rather than intercept values as in the case of R(av), K(av) and BF map coefficients). A plot of 'observed' versus calculated values of $Q_o(1")$ adjusted using the map coefficients is given in Fig. 10.

5.3 Peak Discharge vs Topographic Drainage Area

To assess the value of Equation 5.18 in Table 6, logarithms of peak flow due to 1 ins. of excess precipitation ($Q_o(1")$) was plotted against logarithms of drainage basin area (TDA) (Fig. 11). In spite of the high multiple correlation coefficient (0.94), the predicted value of peak flow varies by as much as a factor of 10 for a given drainage basin area. The values of the random variable Q_o plotted in Fig. 11 were calculated using Eq. 5.7, and therefore, for a given drainage area, effects on peak flow due to differences in hydrograph shape did not manifest

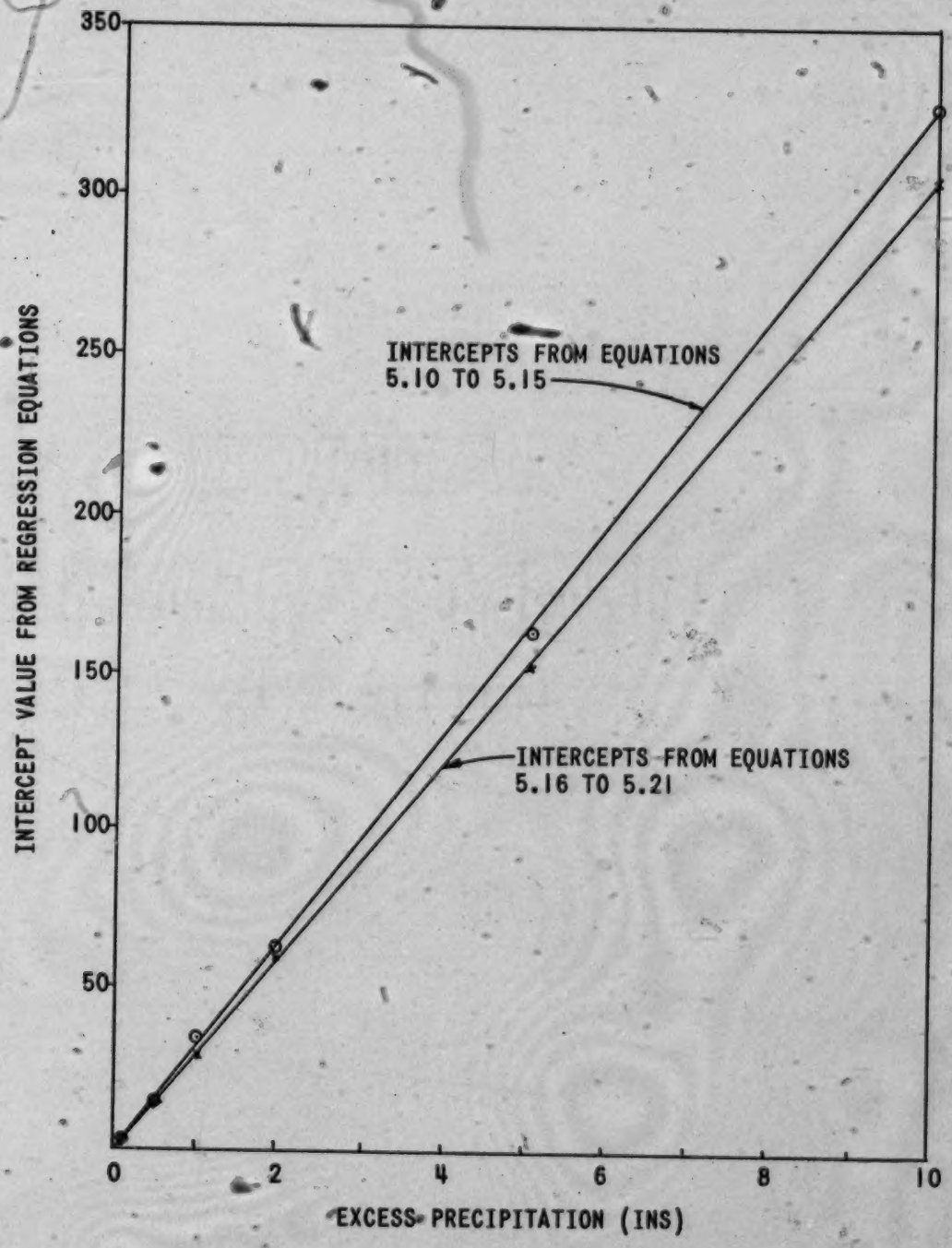


FIG. 8 REGRESSION INTERCEPT VS. DEPTH OF EXCESS PRECIPITATION

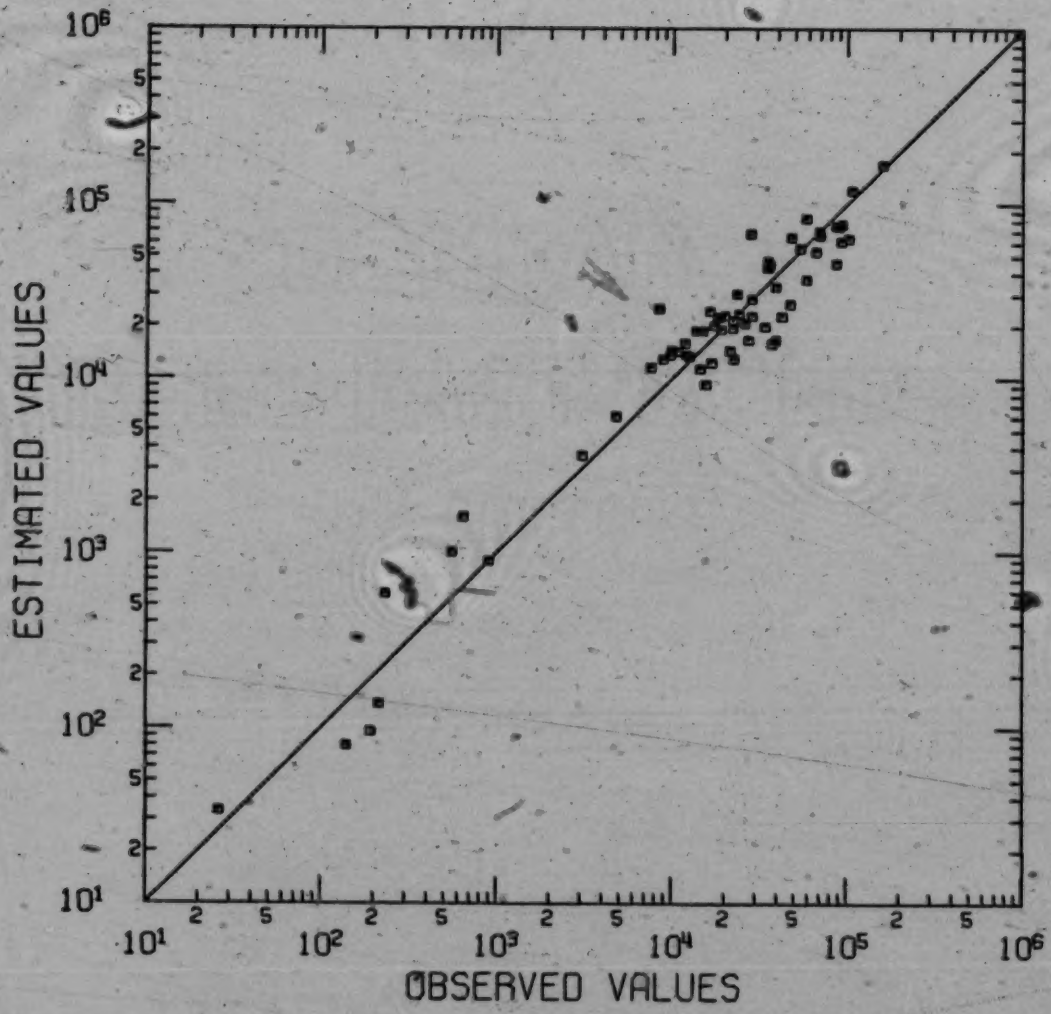


FIG. 9 PEAK FLOW FROM 1 INS EXCESS PPT.: OBSERVED VS. ESTIMATED VALUES BY REGRESSION

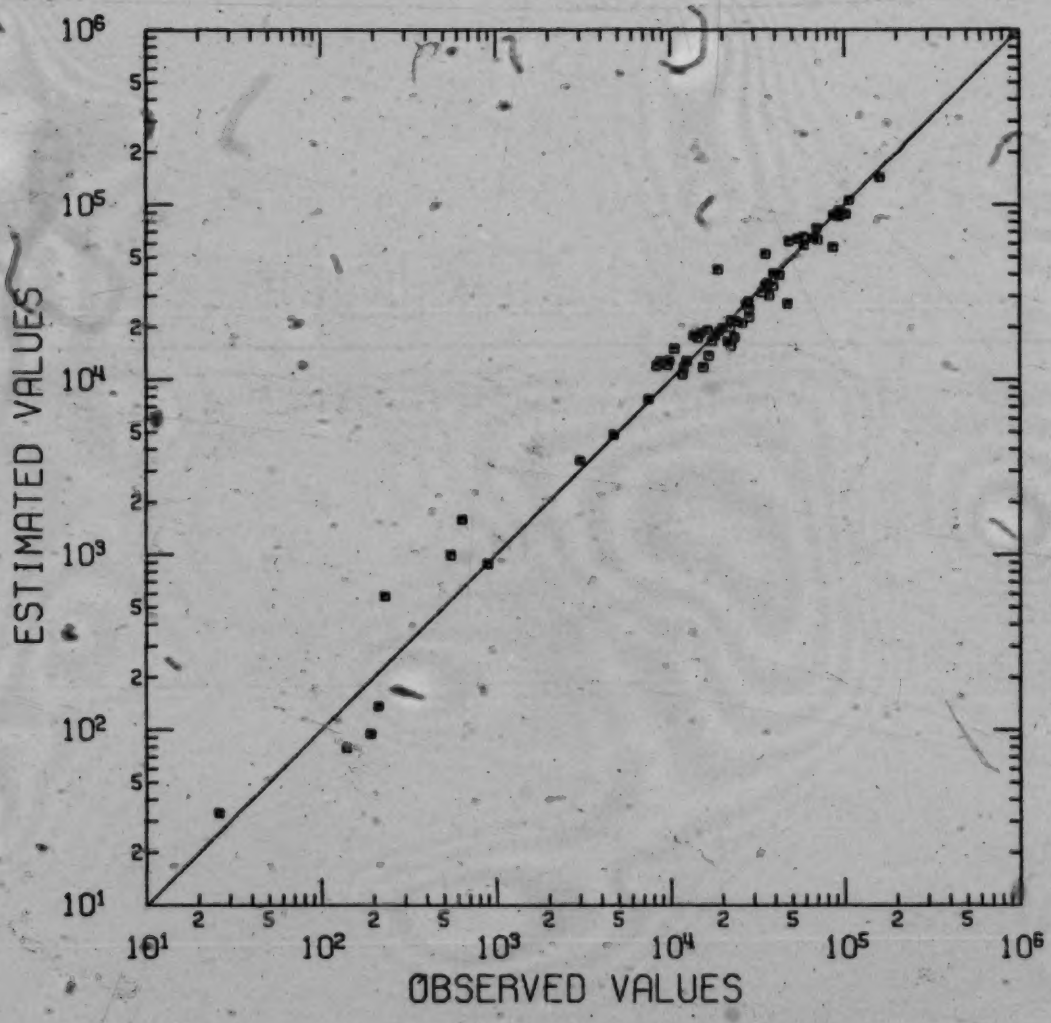


FIG. 10 PEAK FLOW FROM 1 INS EXCESS PPT.: OBSERVED VS. ESTIMATED VALUES BY REGRESSION, ADJUSTED USING MAP COEFFICIENTS

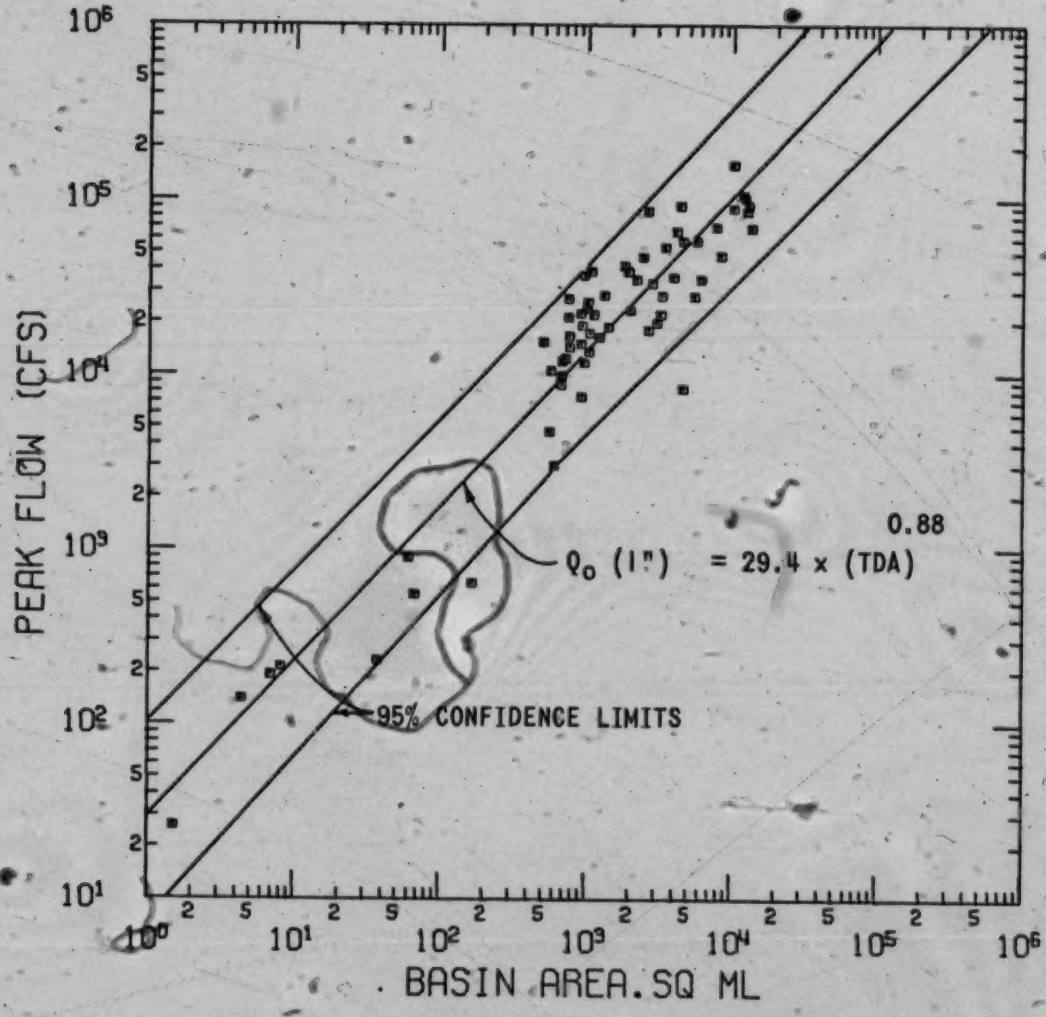
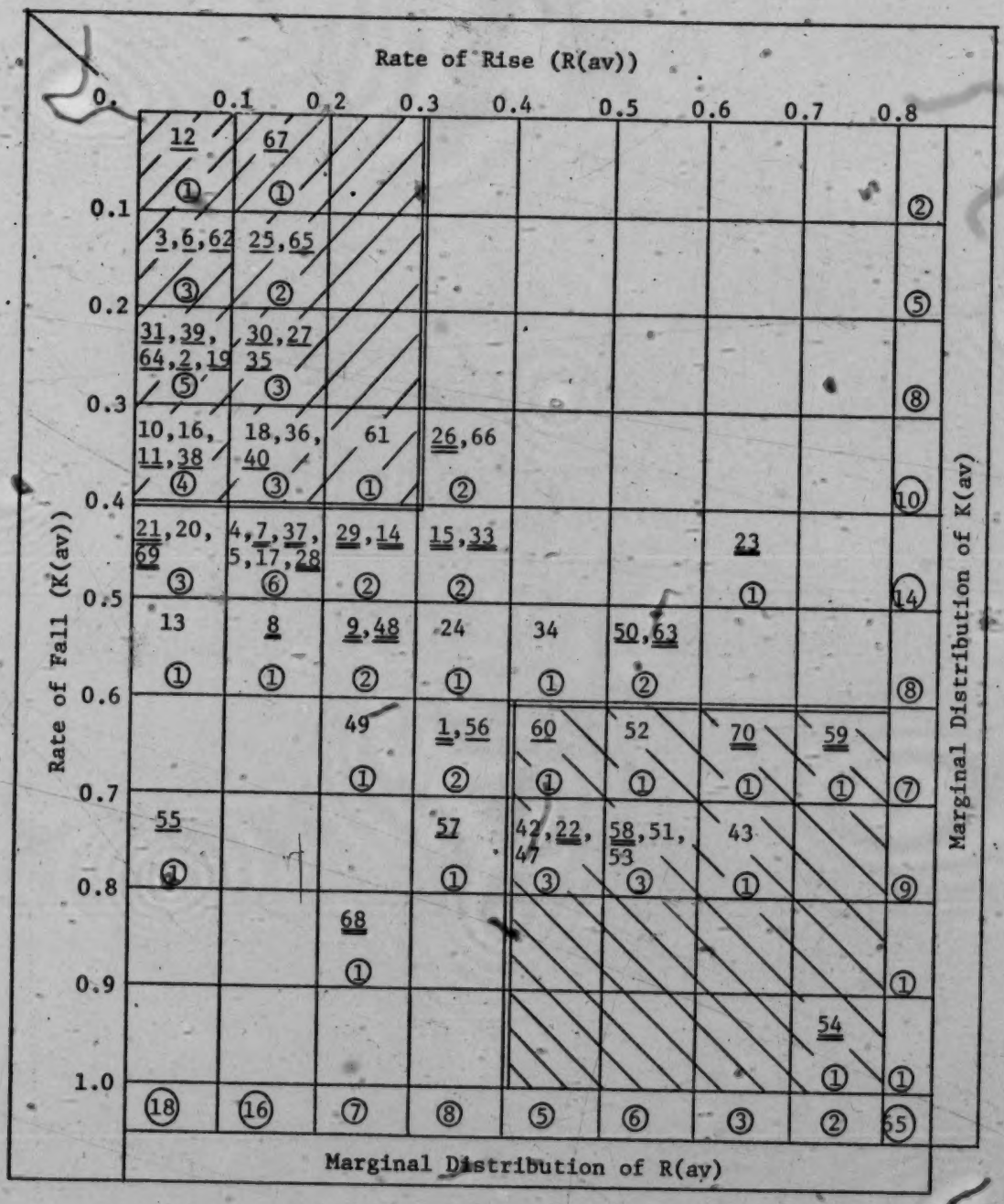


FIG. 11 ESTIMATED PEAK FLOW FROM 1 INS. EXCESS PPT. VS. BASIN AREA

themselves. The spread in Q_o values, for a given basin area and depth of excess precipitation, must be attributable to the rates of rise and drop of discharge and to baseflow (R,K, and BF).

To investigate the effect of different R and K values, Eq. 5.12 was used to calculate $Q_o(1")$ values for each of the study watersheds, using the known basin characteristics. The $Q_o(1")$ values so calculated are called the estimated values. The ratio was found between these estimated $Q_o(1")$ values, and the $Q_o(1")$ values determined using Eq. 5.7 (the 'observed' values). The stations for which the ratio was greater than 1.2 or less than 0.8 were noted. Next, a table was prepared (Table 7), showing the bi-variate distribution of R and K for each of the sample stations. Stations for which the ratio of estimated to observed $Q_o(1")$ values was less than 0.8 were underlined and those for which the ratio was greater than 1.2 were double underlined. Table 7 shows a strong trend; that for those stations having low values of R and K, i.e., steep rising and falling hydrograph limbs, Eq. 5.12 underestimates the value of Q_o. Similarly, Eq. 5.12 overestimates the value of Q_o for those stations with flat hydrographs.

On the basis of Table 7, the sample stations were separated into 3 groups; group 1 consisting of 23 stations with low values of both R and K, group 3 consisting of 12 stations with high values of R and K, and group 2 containing the remaining 30 stations. Regression analyses were then carried out on each group using basin area as the independent variable. The results are given in Table 8 and plotted in Fig. 12. The three multiple correlation coefficients, each in excess of 0.97, indicate the high degree of correlation between peak flow and drainage basin area.



12: Station number where estimated $Q_o(1")$/observed $Q_o(1") < 0.8$

21: " " " " " " " > 1.2

①: Number of observations in each category.

TABLE 7 BI-VARIATE DISTRIBUTION OF R AND K FOR 65 SAMPLE GAUGING STATIONS

Stations Included in Regression Analysis	Regression Equation	Multiple Correlation Coefficient	Equation No.
Group I 23 Stations: $R < 0.3$ and $K < 0.4$	$Q_o(1.0") = 30.5x(TDA)^{0.96}$	0.991	5.22
Group II 30 Stations not included in Groups I or III	$Q_o(1.0") = 14.35x(TDA)^{0.97}$	0.983	5.23
Group III 12 No Stations: $R > 0.4$ and $K > 0.6$	$Q_o(1.0") = 5.47x(TDA)^{1.0}$	0.973	5.24

TABLE 8 REGRESSION EQUATIONS FOR PEAK FLOW VS. TOPOGRAPHIC DRAINAGE AREA, FOR RANGES OF R (av) AND K (av)

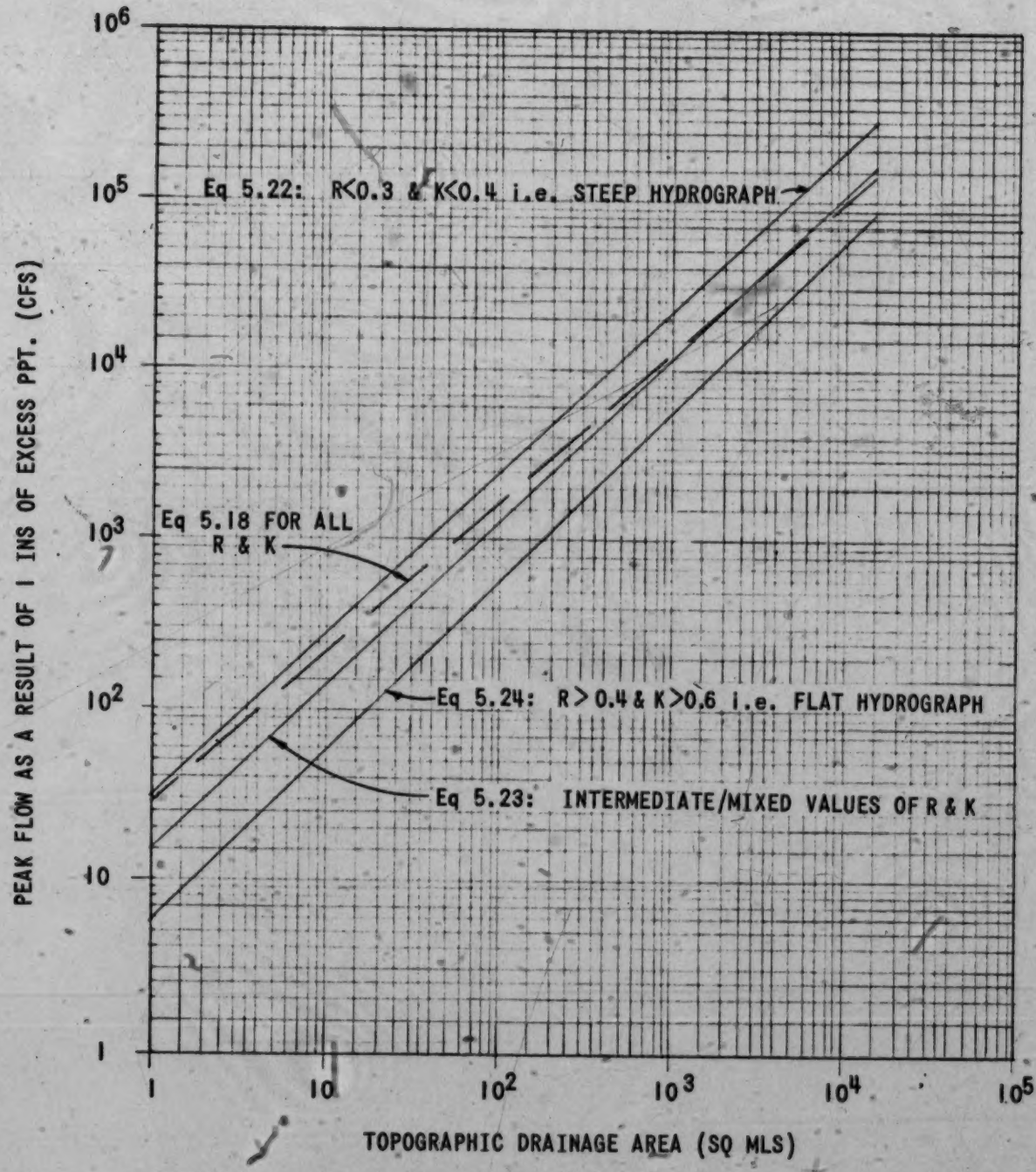


FIG. 12 PEAK FLOW FROM 1 INS OF EXCESS PPT. VS. TOPOGRAPHIC DRAINAGE AREA, FOR RANGES OF R AND K

The equations of Table 8 can be extended and simplified to

$$Q_o = C_1 \times d \times A \qquad \text{Eq. 5.25}$$

where d = average depth of excess precipitation (ins.)

C_1 = 30.5 for basins with steep hydrographs

= 14.3 for basins with mixed hydrographs

= 5.5 for basins with flat hydrographs

5.4 Comparison with Existing Peak Flow Formulae

Many well known peak flow formulae are of the form

$$Q = mA^n \qquad \text{Eq. 5.26}$$

where Q = the peak discharge

A = the basin area

M, n = are coefficients

In order to compare the form of Eq. 5.25 with that of Eq. 5.26, it was necessary to eliminate the parameter d (the maximum depth of excess precipitation occurring over the drainage basin area). Meteorological records for Alberta were searched to find the most severe Maximum Depth Area Curve for the region. The greatest rainfall depth resulted from a storm centred 50 miles southeast of Banff from June 19 - 29, 1969. The depth of precipitation for the total storm duration is plotted on logarithmic axes in Fig. 13. It can be seen that the curve can be approximated, for basin areas less than 10,000 sq. miles, by the equation

$$P = 14.5\ A^{-0.08} \qquad \text{Eq. 5.27}$$

For basin areas between 10,000 sq. miles and 100,000 sq. miles the depth of precipitation is given by the equation

$$P = 320\ A^{-.41} \qquad \text{Eq. 5.28}$$

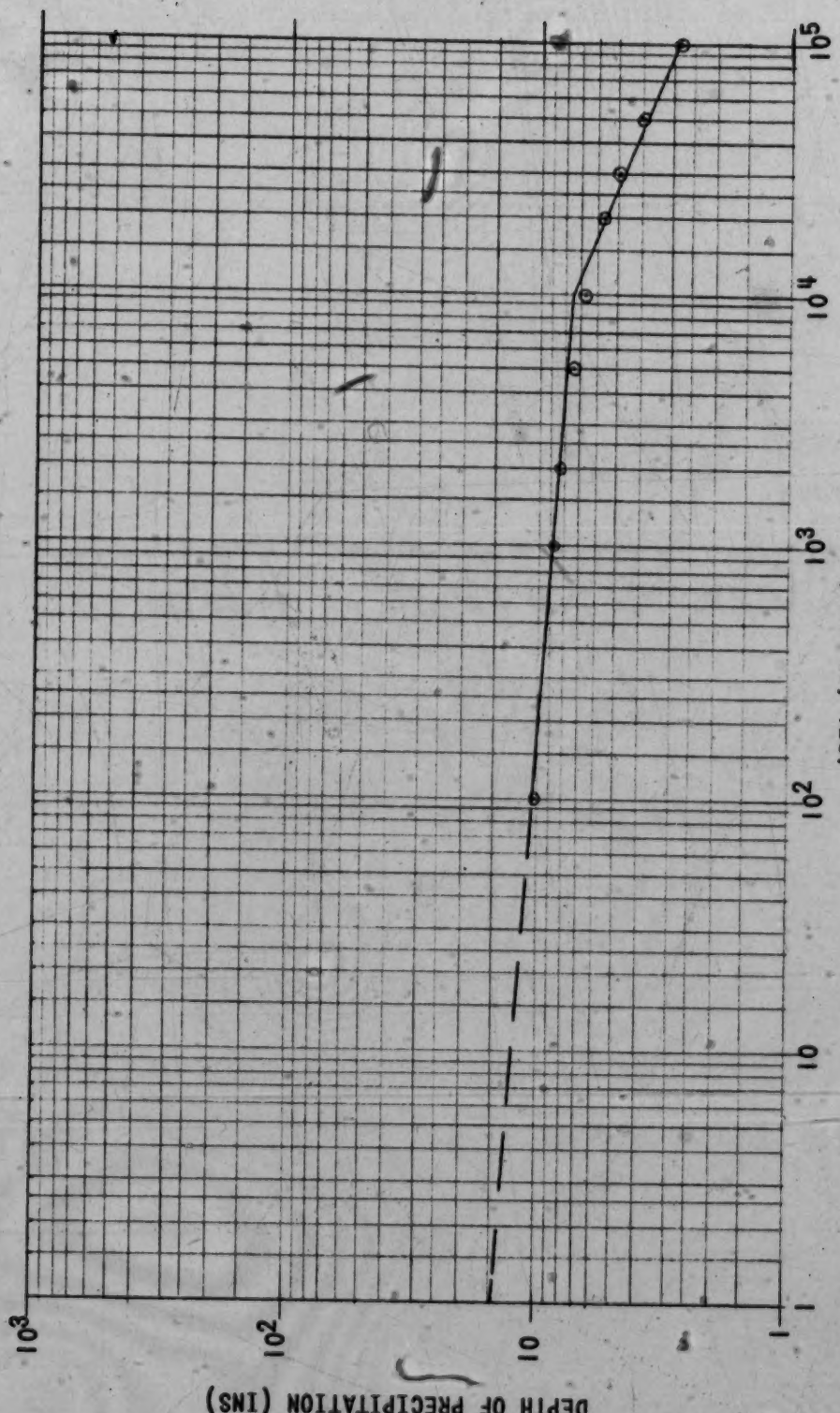


FIG. 13 MAXIMUM DEPTH OF PPT. VS. AREA: STORM JUNE 19-29 1969, NEAR BANFF ALTA.

The depth of excess precipitation (d) equals the depth of precipitation (P) multiplied by a runoff coefficient C. C may be assumed approximately equal to 0.5 .

Then $d = 0.5 \times P$

Substituting for P in Eq. 5.27, for basins less than 10,000 sq. miles,

$$d = 7.25A^{-0.08} \qquad \text{Eq. 5.29}$$

and substituting for P in Eq. 5.28, for basins greater than 10,000 sq. miles

$$d = 160A^{-0.41} \qquad \text{Eq. 5.30}$$

Substituting for d in Eq. 5.23, for basins less than 10,000 sq. miles, whose hydrographs have intermediate slopes

$$Q_o = 14.3 \times 7.25A^{-0.08} \times A^{.97}$$

$$\text{i.e., } Q_o \simeq 100A^{.9} \qquad \text{Eq. 5.31}$$

Similarly, for basins greater than 10,000 sq. miles

$$Q_o = 14.3 \times 160A^{-.41} \times A^{.97}$$

$$\text{i.e., } Q_o \simeq 2{,}300\ A^{.56} \qquad \text{Eq. 5.32}$$

CHAPTER 6

DISCUSSION & CONCLUSIONS

6.1 Discussion

The result of this study is a procedure which enables the determination of the main features of the hydrographs of rare flood events, for ungauged watersheds from 1 to 15,000 sq. miles in area, located in Alberta and southern Yukon Territory.

An important feature of this study is that hydrometric records of the sample watersheds were analyzed without the need for information about the input during the period of record. Such information is not usually readily available. The equations derived allow the determination of the approximate hydrograph shape for different volumes of direct runoff. In order to apply the method to ungauged watersheds, the type of input likely to produce extreme floods on those basins must be determined. A depth of excess precipitation (rain or snowmelt) must also be selected. The frequency with which the selected excess precipitation will occur, gives an indication of the frequency of the peak flow determined from the formulae.

The method is based on a statistical analysis of existing hydrometric records and on two major assumptions, the merits and implications of which will be discussed.

The method assumes that there is a limit to the gradient which can be attained by the rising and falling limbs of the hydrograph of a particular watershed. It is generally agreed that the assumption is approximately true for the falling limb, since this represents the rate of withdrawal of water from storage within the basin, after input

has ceased. The slope of the rising limb, however, is dependent upon the intensity and duration of the input.

Inspection of the composite hydrographs showed that there were sections of the rising limb, having a nearly constant slope over considerable discharge ranges. This slope was virtually the steepest to occur, and indicated that a limiting slope might exist. The occurrence of a limiting slope over a wide discharge range might indicate that the maximum possible input rate occurred or was approached quite often, for short durations.

In larger basins, where channel flow is predominant, the ultimate rate of rise of stream flow may be limited by the increasing amounts of water required in storage to produce the necessary hydraulic head to move the water through the basin, combined with the greater frictional resistance associated with overbank flow. Even if very rare floods have rising limbs somewhat steeper than that indicated by the available period of record, it can be seen from the equations of Table 8 that peak flow is not highly sensitive to variations in hydrograph slope.

The second assumption made, is that the limiting rates of rise and fall of the hydrograph limbs are virtually straight when plotted as logarithms of discharge versus time. This implies that the discharge on any day is a fixed proportion of the discharge on the preceding day. The composite hydrographs produced during the course of this study indicate that this is approximately true for considerable ranges of discharge.

It is interesting to compare the implications of these assumptions with those of unit hydrograph theory. It will be recalled that a unit hydrograph has a fixed time base, i.e., the time to peak flow and

the time for recession are constant for a fixed input duration, regardless of the volume of excess precipitation. This implies that, for increasing runoff, the rates of rise and drop also increase. However, it is generally accepted that there is a limit to the recession rate, governed by the physical characteristics of the basin. Thus, if the volume of runoff is taken sufficiently large, the recession limb becomes steeper than is physically possible. It seems more realistic that a larger volume of water in storage will take longer to drain, once input has ceased, than will a smaller volume, so that the recession period should increase with increasing excess precipitation.

As to the rising limb, neither a fixed time to peak flow as in unit hydrograph theory, nor a constant rate of rise, can be justified theoretically. The implications of a constant rate of rise are: -

a) that the time to peak flow increases as the volume of runoff increases,

and b) that at a particular time after the beginning of runoff, the discharge will be same for any flood considered.

With reference to a) above, since the mean value of the rate of rise (R) for the 62 basins studied is approximately 0.25, the discharge on one day is about four times that on the previous day. This means that for increasing runoff volumes, the peak discharge increases rapidly but the time to peak increases slowly. A slight increase in the time to peak, with increasing runoff, has been noted by several authors. (Linsley, 1958).

With reference to b) above; considering that the procedure is limited to 'extreme' flood events, the concept of a fixed discharge

after a certain time is not unreasonable. Possibly, the real relationship between discharge and time, during the rising portion of the hydrograph, lies between these two extremes. However, the concept of a fixed rate of rise is a good approximation and has the merit of simple mathematical representation.

An interesting feature of composite hydrographs produced from existing records, was the occurrence of a quite definite base flow discharge. It appears that, at the cessation of direct runoff, river discharge is maintained at a constant level due to the influx of groundwater. It would require an extremely rare drought situation to affect the baseflow discharge. For small basins in general, and for those of the prairies in particular, the baseflow discharges are zero.

The two assumptions discussed previously, together with the occurrence of a distinct baseflow discharge, lead to the idealized hydrograph of Fig. 7 (triangular when plotted to semilogarithmic scale). A feature of this hydrograph, and a source of error, was the elimination of a crest-section. Consideration was given to determining a crest width from the composite hydrographs for each study basin, and carrying out a regression analysis against the basin characteristics. However, the crest section of each composite hydrograph was derived from a single storm (see Section 2.4) and was not necessarily representative. An analysis of many crest segments for each basin could be required to accurately assess the crest shape. Such an analysis was beyond the scope of this study.

Regression analysis showed that, as expected, the selected hydrograph parameters are related to watershed characteristics. The characteristics included in the analysis were limited to those for which data exists or can readily be determined. This precluded such factors

as soil distribution and properties, and details of vegetation cover. The regression analysis on the hydrograph shape parameters was moderately productive; regression equations were produced whose multiple correlation coefficients ranged from 0.72 to 0.86. Later analysis showed this to be sufficient.

Equation 5.7 gives a relationship between peak flow (Q_o) and average depth of excess precipitation (d) rates of rise and fall (R and K) baseflow discharge (Q_1) and basin area (TDA). The equation is non-linear and theoretically will produce results which differ from the unit hydrograph concept of peak flow being directly proportional to depth of excess precipitation. However, for a particular watershed, the rates of rise and drop are assumed constant and the baseflow discharge is very much smaller than peak flow for any practical depth of runoff. Therefore, the first and last terms of Equation 5.7 become insignificant and an almost linear relationship between peak flow and runoff depth results. (Table 5 and Fig. 8).

A comparison of the equations in Tables 5 and 6 shows that basin area explains a large portion of the variation between peak flow and the basin characteristics. This is because, not only does basin area appear directly in Equation 5.7, but it contributes significantly to the explained variation of the rates of rise and drop.

It might appear from Table 6 that basin area alone is sufficient to predict peak flow accurately, but the effects of hydrograph shape cannot be ignored. Consequently, three equations have been presented (Table 8) for different ranges of R and K, allowing the determination of peak flow from basin area, for a given depth of excess precipitation.

Analysis of individual storms over the Canadian prairies (Gray, 1970) yields equations, relating peak flow with basin area, of the form

$$Q_o = C \times A^{0.5}$$

where C ranges from 300 to 2,300

and A ranges from 0.1 to 1,000 sq. mls.

A comparison of the above with Eq. 5.31 shows that, for basins less than about 10 sq. mls., the formulae derived in this study give values of peak flow less than those experienced on the prairies, but for basins up to 1,000 sq. miles, this study indicates somewhat higher flows.

A general formula applicable to the U.S.A. (U.S. Geological Survey for Columbia) for basins between 1,000 and 24,000 sq. miles is

$$Q_o = 1400\ A^{0.476}$$

which is in reasonable agreement with Equation 5.32 ($Q_o = 2,300\ A^{.56}$) for basins greater than 10,000 sq. miles.

6.2 Procedure to Determine Hydrograph Shape for Ungauged Watersheds

Depending on the amount and accuracy of the information required, the results of this study can be used to determine the hydrograph for an ungauged watershed in several ways: -

1. i) Determine required depth of excess precipitation from meteorological records

   ii) For the watershed, determine RAIN, TDA, FA, MCL, RE, and MCS according to the definitions of Table 1.

   iii) Determine rates of rise and drop (R and K) and baseflow discharge (BF) from Equations 4.11, 4.12 and 4.13 using the map coefficients appropriate to the basin location.

   iv) Substitute the above values in equation 5.7 and solve for

Q_o using an iterative process.

2. i) to iii) as above

   iv) Determine BA(Y) and solve the appropriate equation of Table 5 to find Q_o, interpolating as necessary

3. i) to iii) as above

   iv) with the appropriate value of R and K, determine Q_o from Fig. 12. Having determined Q_o, and knowing R and K, the hydrograph may be drawn to determine the time distribution of runoff.

4. If only the peak flow is required, R and K can be estimated from a knowledge of basin characteristics, and Q_o determined from Fig. 12 directly. In such a case, R and K need only be determined as high, intermediate/mixed or low.

6.3 Conclusions

A method has been derived to determine the shape of a hydrograph for an ungauged watershed in the Alberta/Yukon region of Canada, for a given depth of excess precipitation. The slopes of the rising and falling limbs are determined from the physical and meteorological characteristics of the watershed, and provide two numerical parameters for watershed classification.

The assumption of constant rates of rise and drop was shown to be reasonable by visual inspection of hydrographs derived from many years of flow records. This assumption implies that the time for runoff to occur increases as the depth of excess precipitation increases and differs from the unit hydrograph theory premise of a constant runoff time. However, the unit hydrograph theory assumption that peak flow is directly proportional to excess precipitation was substantiated.

For small watersheds, meaningful results can be derived only from analysis of instantaneous hydrographs; too much detail being lost when mean-of-the-day discharges are computed.

Only a moderate linear association could be determined between the hydrograph parameters and the selected watershed characteristics but determination of map coefficients, to reduce the effect of variables not included in the analysis, improved the usefulness of the equations for predictive purposes. However, the most important parameter, peak flow, was found to have a strong linear association with drainage basin area. The regression equations allow the rates of rise and fall to be determined with sufficient accuracy for peak flow values to be determined for a range of hydrograph shapes.

6.4 Suggestions for Further Study

1. If sufficient data could be accumulated, hydrograph analysis of watersheds in a smaller geographic region might produce stronger associations with basin characteristics, and hence increase the predictive value of the regression equations.
2. A study might be undertaken to correlate flood hydrograph crest shape with basin characteristics to make the triangular hydrograph, used in this analysis, more realistic.
3. A comparison might be made of the values of R(av) and R(max) (Section 2.4) to determine whether they approach the same value, as the length of discharge record increases. A similar analysis could be undertaken for K(av) and K(max). Such an analysis could verify the assumption of a limiting slope for the rising and falling hydrograph limbs.

4. The computer programs developed for this study could be used to determine R and K for different times of the year. Time of the year could then be introduced into the regression analysis and the resulting equations used to determine peak flows at different seasons.

BIBLIOGRAPHY

Bethlahmy, N. "Water Yield, Annual Peaks and Exposure in Mountainous Terrain." U.S.D.A., Forest Service, Intermountain Forest and Range Experiment Station, Moscow, Idaho, 1973.

Chow, V.T. "Handbook of Applied Hydrology.", McGraw-Hill Book Co., Inc., New York, 1964.

Creager, W.P., Justin, J.D. and Hinds, J. "Engineering for Dams.", Vol. I, John Wiley and Sons Inc., New York, 1945.

DeCoursey, D.G., "A Runoff Hydrograph Equation", Agric. Res. Service, ARS 41-116, Feb. 1966.

Edson, C.G. "Parameters for Relating Unit Hydrographs to Watershed Characteristics.", Trans. Amer. Geoghys. Union. Aug. 1951 pp. 591 - 596.

Gray, D.M., Editor-in-chief, "Handbook on the Principles of Hydrology.", Secretariate, Can. Nat. Com. for the Int. Hydrological Decade Ottawa, 1970.

Gupta, V.L. and Moin, S.A. "Surface Runoff Hydrograph Equation.", Journal of Hydraulics Div., ASCE, Oct. 1974.

Hudlow, M.D. and Clarke, R.A. "Hydrograph Synthesis by Digital Computer.", Journal Hydraulics Div., ASCE, May 1969 pp. 839 - 860.

Koelzer, V.A. and Bitoun, M. "Hydrology of Spillway Design Floods: Large Structures - Limited Data.", Journal of Hydraulics Div., ASCE May 1964.

Leaf, C.F. and Brink, G.E. "Hydrologic Simulation Model of Colorado Subalpine Forest." U.S.D.A., Forest Service Research Paper RM107 Ft. Collins, Colorado, May 1973.

Linsley, R.K., Jr., Kohler, M.A. and Paulhus, J.L.M. "Hydrology for Engineers.", McGraw-Hill Book Co., Inc., New York, 1958.

Nash, J.E., "The Form of the Instantaneous Unit Hydrograph.", IASH General Assembly of Toronto, Vol. III 1957 pp. 114-121.

Poliquin, W.H. and Hanson, W.R. "Precipitation on the East Slopes of the Rockies in Alberta.", E. Rockies For. Consery. Board, Management Report No. 3, March 1973.

Sly, W.K. "A Climatic Moisture Index for Land and Soil Classification in Canada.", Canadian Journal of Soil Sci. pp 291 - 301, Oct. 1970

BIBLIOGRAPHY (CONT.)

Smillie, K.W. "An Introduction to Regression and Correlation.", University of Alberta, Dept. of Computer Science, 1965.

Spence, E.S. "Streamflow Analysis in the Canadian Plains.", Ph.D. Thesis. University of Alberta, Edmonton, 1971.

Verschuren, J.P. and Bristol, M. "Runoff from Small Watersheds and River Bank Erosion Near Watson Lake, Y.T.", ALUR 73 - 74 - 02, Ind. and N. Affairs Publication No. QS-1585-000-EE-A1, Ottawa, 1974.

Verschuren, J.P. and Qazi, M.E. "Hydrograph Shape as a Function of Drainage Basin Characteristics for Selected Rivers in N.W. Canada.", ALUR 72 - 73 - 42, Ind. and N. Affairs Publication No. Qs-3035-000-EE-A1, Ottawa, 1973.

Yevjevich, V. "Probability and Statistics in Hydrology.", Water Resources Publications, Fort Collins, Colorado, 1972.

APPENDIX I

COMPUTER PROGRAMS

```
C
C                    PROGRAM "SLOPE"
C
C     TO COMPUTE CO-ORDINATES OF THE STEEPEST POSSIBLE HYDROGRAPH FROM
C     EXISTING DISCHARGE RECORDS AT ANY GAUGING STATION WHERE THE
C     GIVEN DISCHARGE VALUES ARE SPACED AT REGULAR TIME INTERVALS.
C
C     Q=INPUT VECTOR OF DISCHARGE VALUES.
C     ALPH=HEADING FOR OUTPUT (ALSO USED FOR HYDROGRAPH PLOT TITLES.)
C     X AND Y =OUTPUT VECTORS OF HYDROGRAPH CO-ORDINATES.
      REAL NSPAN,NGRAD
      DIMENSION Q(3000),QPAIR(2,3000),QS(2,3000),
     *NSPAN(500),NGRAD(500),ALPH(20),Y(3000),R(500),D(500),
     *DROPS(3000),RISE(3000),Y2(3000),QP(2,3000),X(3000)
C
C     READ DISCHARGE DATA (MONTHS N1-N2 INCL. ONLY)
C     NM IS NUMBER OF MONTHS OF DATA ON FILE
C     IF DATA READ FROM FILE WRITTEN BY "ADD", ADD=1.0
      READ (5,10) NM,N1,N2, ADD
   10 FORMAT(3I6,F6.0)
      NSTART=1
      WRITE(3,1) NSTART
    1 FORMAT(1X,I6)
      JP9=0
      JP10=0
      J=2
      Q(1)=-999.
      IF (ADD .EQ. 1.0) GO TO 3
      DO 25 N=1,NM
      DO 26 II=1,2
      JP9=J+9
      READ(4,11)L,M,(Q(I),I=J,JP9)
   11 FORMAT (11X,I2,I1,(10F6.0))
      IF (N.EQ.1 .AND. II .EQ. 1 .AND. M .NE. 1) GO TO 13
      GO TO 15
   13 WRITE (6,14)
   14 FORMAT(' ','DATA DOES NOT START AT BEGINNING OF MONTH')
      GO TO 970
   15 IF(N1 .LE. N2 .AND. (L .LT. N1 .OR. L .GT. N2)) GO TO 26
      IF(N1 .GT. N2 .AND. (L .LT. N1 .AND. L .GT. N2)) GO TO 26
      J=JP9+1
   26 CONTINUE
      JP10=J+10
      READ (4,12) L,(Q(I),I=J,JP10)
   12 FORMAT (11X,I2,1X,(11F6.0))
      IF(N1 .LE. N2 .AND. (L .LT. N1 .OR. L .GT. N2)) GO TO 24
      IF(N1 .GT. N2 .AND. (L .LT. N1 .AND. L .GT. N2)) GO TO 24
      J=JP10+1
      GO TO 25
   24 Q(J)=-999.
      J=J+1
   25 CONTINUE
      Q(J)=-999.
      Q(J+1)=-999.
      GO TO 4
    3 READ(4,16) K
   16 FORMAT(I7)
      J=K+1
      READ(4,20) (Q(I),I=2,J)
   20 FORMAT (1X,10F7.0)
      Q(J+1)=-999.
      J=J+1
    4 IF (J-3000) 2,2,8
    8 WRITE(6,9)
    9 FORMAT(' ','NO. OF DATA POINTS EXCEEDS 3000.')
      GO TO 970
C
C     WRITE HEADING
    2 READ(5,5) (ALPH(I),I=1,20)
    5 FORMAT (20A4)
      WRITE (6,6) (ALPH(I),I=1,12)
```

```
      6     FORMAT (1H1,6X,20A4)
            WRITE (3,7) (ALPH(I),I=1,20)
      7     FORMAT(' ',20A4)
      C
      C     TAKE COMMON LOGS OF DISCHARGE VALUES
            DO 46 I=1,J
            IF (Q(I)) 46,45,45
     45     IF (Q(I).LE.1.0) Q(I)=1.001
            Q(I)=ALOG10(Q(I))
     46     CONTINUE
     21     FORMAT(' ',F10.4)
      C
      C     DELETE MISSING DATA
      C     LIST PAIRS OF DISCHARGES ON CONSECUTIVE DAYS
            M=0
            DO 70 I=2,J
            IF (Q(I)) 60,50,50
     50     M=M+1
            QP(1,M)=Q(I)
            QP(2,M)=Q(I+1)
            GO TO 70
     60     IF (Q(I-1).GE.0.0) M=M-1
     70     CONTINUE
            DO 75 I=1,M
            QS(1,I)=QP(1,I)
            QS(2,I)=QP(2,I)
     75     CONTINUE
            WRITE(6,36) M
     36     FORMAT(' '//6X,'NO. OF PAIRS OF CONSEC. DISCHARGE VALUES=',I6)
    125     FORMAT(' '//I6,2F10.4)
      C
      C     SEPARATE PAIRS INTO +VE (QP) AND -VE (QPAIR) SLOPES
            JJ=0
            MM=0
            DO 99 I=1,M
            IF (QS(2,I).GT.QS(1,I)) GO TO 98
            JJ=JJ+1
            QPAIR(1,JJ)=QS(1,I)
            QPAIR(2,JJ)=QS(2,I)
            GO TO 99
     98     MM=MM+1
            QP(1,MM)=QS(1,I)
            QP(2,MM)=QS(2,I)
     99     CONTINUE
      C
      C     FIND LOCAL MINIMAS & DISCONTINUITIES
            N=0
            N2=0
            N3=0
            DO 100 I=2,M
            A=QS(1,I)
            B=QS(2,I)
            C=QS(1,I-1)
            E=QS(2,I-1)
            IF ((A.EQ.E).AND.(B.GT.A).AND.(C.GT.A)) GO TO 101
            IF ((A.NE.E).AND.(B.GE.A)) GO TO 102
            IF ((A.NE.E).AND.(B.LE.A)) GO TO 103
             GO TO 100
    101     N=N+1
            Y2(N)=A
            GO TO 100
    102     N2=N2+1
            R(N2)=A
            GO TO 100
    103     N3=N3+1
            D(N3)=E
    100     CONTINUE
      C
      C     RECESSION LIMB
      C
      C     ORDER QPAIR ON 1ST ROW
            CALL SORTRO(QPAIR,2,JJ,1)
```

```
145     C
146     C       DETERMINE POINTS TO BE USED IN SEARCH
147             DO 108 I=1,N
148             QS(1,I)=Y2(I)
149             QS(2,I)=Y2(I)
150     108     CONTINUE
151             DO 104 I=1,JJ
152             QS(1,N+I)=QPAIR(1,I)
153             QS(2,N+I)=QPAIR(2,I)
154     104     CONTINUE
155             NI=N+I
156             IF (N3) 105,105,107
157     107     DO 105 J=1,N3
158             QS(1,NI+J)=D(J)
159             QS(2,NI+J)=D(J)
160     105     CONTINUE
161             NJ=NI+N3
162             CALL SORTRO(QS,2,NJ,1)
163     C
164     C       COMPUTE RANGES SPANNING EACH DISCHARGE VALUE
165             L1=0
166             DO 200 I=1,NJ
167             K=0
168             DO 150 J=1,JJ
169             Q1J=QPAIR(1,J)
170             Q2J=QPAIR(2,J)
171             Q1I=QS(1,I)
172             Q2I=QS(2,I)
173             IF (Q1J.LT.Q1I) GO TO 129
174             IF (Q1J.GE.Q1I.AND.Q2J.LT.Q1I) GO TO 160
175     128     FORMAT(2I6)
176             GO TO 150
177     160     K=K+1
178             NSPAN(K)=Q1J
179             NGRAD(K)=Q2J-Q1J
180     150     CONTINUE
181     C
182     C       SELECT STEEPEST GRAD. FOLLOWING DISCHARGE VALUE
183     129     IF(K) 130,200,130
184     130     GRI=Q2I-Q1I
185             TEMP=GRI
186             L1=L1+1
187             DO 210 J=1,K
188             IF (NGRAD(J).LE.TEMP) GO TO 300
189             GO TO 210
190     300     KK=J
191             TEMP=NGRAD(J)
192     210     CONTINUE
193     C
194     C       LIST DESCENDING DISCHARGE VALUES& STEEPEST FOLLOWING GRAD.
195             IF (L1.EQ.1) GO TO 250
196             IF (TEMP-X(L1-1)) 220,230,240
197     220     X(L1)=TEMP
198             Y(L1)=NSPAN(KK)
199             GO TO 200
200     230     Y(L1)=Y(L1-1)
201             X(L1)=X(L1-1)
202             GO TO 200
203     240     X(L1)=TEMP
204             Y(L1)=Q1I
205             GO TO 200
206     250     Y(1)=Q1I
207             X(1)=TEMP
208     200     CONTINUE
209     C
210     C       CONDENSE LIST OF ORDINATES
211             Q(1)=Y(1)
212             DROPS(1)=X(1)
213             L2=1
214             DO 310 I=2,L1
215             IF (Y(I).EQ.Q(L2)) GO TO 310
216             L2=L2+1
```

```
217             Q(L2)=Y(I)
218             DROPS(L2)=X(I)
219      310    CONTINUE
220      131    FORMAT(F10.4)
221             WRITE(6,315) L2
222      315    FORMAT(' '//6X,'ORIGINAL NO. OF POINTS ON RECESSION LIMB=',I6)
223      C
224      C      RISING LIMB
225      C      ORDER QP ON 2ND ROW
226             CALL SORTRO(QP,2,MM,2)
227      C
228      C      DETERMINE POINTS TO BE USED IN SEARCH
229             DO 405 I=1,N
230             QS(1,I)=Y2(I)
231             QS(2,I)=Y2(I)
232      405    CONTINUE
233             DO 400 I=1,MM
234             QS(1,N+I)=QP(1,I)
235             QS(2,N+I)=QP(2,I)
236      400    CONTINUE
237             NI=N+I
238             IF (N2) 401,401,402
239      402    DO 401 J=1,N2
240             QS(1,NI+J)=R(J)
241             QS(2,NI+J)=R(J)
242      401    CONTINUE
243             NJ=NI+N2
244             CALL SORTRO (QS,2,NJ,2)
245      C
246      C      COMPUTE RANGES SPANNING EACH DISCHARGE VALUE
247             L1=0
248             DO 500 I=1,NJ
249             K=0
250             DO 650 J=1,MM
251             QP2J=QP(2,J)
252             QP1J=QP(1,J)
253             QP1I=QS(1,I)
254             QP2I=QS(2,I)
255             IF (QP2J.LT.QP2I) GO TO 653
256             IF (QP2J.GE.QP2I.AND.QP1J.LT.QP2I) GO TO 560
257             GO TO 650
258      560    K=K+1
259             NSPAN(K)=QP2J
260             NGRAD(K)=QP2J-QP1J
261      650    CONTINUE
262      651    FORMAT(I6,(2F10.4))
263      C
264      C      SELECT STEEPEST GRAD. PRECEEDING DISCHARGE VALUE
265      653    IF (K) 652,500,652
266      652    GRI=QP2I-QP1I
267             TEMP=GRI
268             L1=L1+1
269             DO 710 J=1,K
270             IF (NGRAD(J).GE.TEMP) GO TO 800
271             GO TO 710
272      800    KK=J
273             TEMP=NGRAD(J)
274      710    CONTINUE
275      C
276      C      LIST DESCENDING DISCHARGE VALUES & STEEPEST PRECEEDING GRAD.
277             IF (L1.EQ.1) GO TO 730
278             IF (TEMP-X(L1-1)) 720,760,740
279      740    X(L1)=TEMP
280             Y(L1)=NSPAN(KK)
281             GO TO 500
282      720    X(L1)=TEMP
283             Y(L1)=QP2I
284             GO TO 500
285      760    Y(L1)=Y(L1-1)
286             X(L1)=X(L1-1)
287             GO TO 500
288      730    Y(1)=QP2I
```

```
      X(1)=TEMP
500   CONTINUE
C
C     CONDENSE LIST OF ORDINATES
      Y2(1)=Y(1)
      RISE(1)=X(1)
      L3=1
      DO 750 I=2,L1
      IF (Y(I).EQ.Y2(L3)) GO TO 750
      L3=L3+1
      Y2(L3)=Y(I)
      RISE(L3)=X(I)
750   CONTINUE
      WRITE(6,755) L3
755   FORMAT(' '//6X,'ORIGINAL NO OF POINTS ON RISING LIMB=',I6)
C
C     PREPARE DATA FOR PLOTTING
      X(1)=0.0
      Y(1)=Y2(L3)-RISE(L3)
      L=1
      DO 810 I=1,L3
      L=L+1
      Y(L)=Y2(L3-I+1)
      X(L)=X(L-1)+((Y(L)-Y(L-1))/RISE(L3-I+1))
810   CONTINUE
      Y(L+1)=Q(1)
      IF (Y(L)-Q(1)) 820,830,840
820   X(L+1)=X(L)+((Y(L+1)-Y(L))/RISE(1))
      GO TO 850
830   X(L+1)=X(L)
      GO TO 860
840   X(L+1)=X(L)+((Y(L+1)-Y(L))/DROPS(1))
850   L4=L+1
      DO 860 I=2,L2
      L4=L4+1
      Y(L4)=Q(I)
      X(L4)=X(L4-1)+((Y(L4)-Y(L4-1))/DROPS(I-1))
860   CONTINUE
      Y(L4+1)=Y(L4)+DROPS(L2)
      X(L4+1)=X(L4)+1.0
      L5=L4+1
      WRITE (6,891) L5
891   FORMAT(' '//6X,'ORIGINAL NO. OF DATA POINTS=',I6)
C
C     FIND RANGE OF LOG-DISCHARGE VALUES
      R(1)=AMIN1(Y(1),Y(L5))
      R(2)=AMAX1(Q(1),Y2(1))
      HITE=R(2)-R(1)
      WRITE(6,55) R(2),R(1),HITE
55    FORMAT(' '//6X,'RANGE OF LOG-DISCHARGE VALUES=',F7.4,' MINUS',F7.4
     *,'=',F7.4)
      D(1)=AINT(R(1))
      D(2)=AINT(R(2))+1.0
      WRITE(6,746) D(1),D(2)
746   FORMAT(' '//6X,'ORDINATE RANGE IS FROM 10**',F4.1,' TO 10**',F4.1)
      WRITE (3,747) D(1),D(2)
747   FORMAT(' ',2F10.4)
C
C     REDUCE NO. OF PLOT POINTS TO 500
      DIST=X(L5)-X(1)
      DEN=1000.0
      N=1
      L6=L5
      GO TO 895
896   L6=N
      N=1
895   IF (L6-500) 950,950,910
910   Q(1)=Y(1)
      Y2(1)=X(1)
      DEN=DEN/2.0
      DO 920 I=2,L6
      IF (ABS(Y2(N)-X(I)).LE.DIST/DEN.AND.ABS(Q(N)-Y(I)).LE.HITE/DEN)
```

```
      *GO TO 920
       N=N+1
       Y2(N)=X(I)
       Q(N)=Y(I)
  920  CONTINUE
  921  FORMAT(' ',I6)
       DO 940 I=1,N
       X(I)=Y2(I)
       Y(I)=Q(I)
  940  CONTINUE
       IF (N.GT.500) GO TO 896
       L5=N
  950  CONTINUE
C
C      FOR DATA PREPARED BY "ADD", CONVERT BACK TO WHOLE DAYS
       IF (ADD .EQ. 0.0) GO TO 951
       DO 952 I=1,L5
       X(I)=X(I)/2.0
  952  CONTINUE
C
C      TAKE ANTI-LOGS OF DISCHARGE TO PLOT ON SEMI-LOG SCALE
  951  DO 870 I=1,L5
       Y(I)=(10.0**Y(I))+0.02
  870  CONTINUE
C
       WRITE (3,960) L5
       WRITE(6,890) L5
  890  FORMAT(1H //6X,'NUMBER OF DATA POINTS TO BE PLOTTED=',I6)
  880  FORMAT(1H //10X,'TIME(DAYS)  DISCHARGE(CFS)')
       WRITE (6,880)
       WRITE(6,960) ((I,X(I),Y(I)),I=1,L5)
       WRITE(3,960) ((I,X(I),Y(I)),I=1,L5)
  960  FORMAT (' ',I6,F12.4,F14.0)
  965  FORMAT(' ',I6,2F12.4)
       GO TO 975
  970  STOP 4
  975  STOP
       END
```

```
      C            PROGRAM "ADD"
      C
      C     TO FABRICATE A DISCHARGE RECORD BY INTERPOLATING DISCHARGE VALUES
      C     AT HALF-DAY INTERVALS FROM THE CO-ORDINATES OF UP TO FIVE SUB-
      C     PERIOD HYDROGRAPHS.
      C
      C     X AND Y = SUB-PERIOD HYDROGRAPH CO-ORDINATES.
      C     QQ=OUTPUT DISCHARGE VALUES INTERPOLATED AT HALF-DAY INTERVALS.
      C
            DIMENSION X(500),Y(500),QQ(1000),Q1(500)
    5       FORMAT(///I7)
   10       FORMAT(7X,F12.4,F14.0)
            READ(8,12) N
   12       FORMAT(24X,I6)
            J=0
            DO 40 II=1,N
            GO TO (6,7,8,9,13), II
    6       READ(1,5) N1
            READ(1,10) (X(I),Y(I),I=1,N1)
   70       FORMAT(' ',2F10.4)
            GO TO 15
    7       READ(2,5) N1
            READ(2,10) (X(I),Y(I),I=1,N1)
            GO TO 15
    8       READ(3,5) N1
            READ(3,10) (X(I),Y(I),I=1,N1)
            GO TO 15
    9       READ(4,5) N1
            READ(4,10) (X(I),Y(I),I=1,N1)
            GO TO 15
   13       READ(9,5) N1
            READ(9,10) (X(I),Y(I),I=1,N1)
      C
      C     INTERPOLATE VALUES AT HALF-DAY INTERVALS
   15       DO 20 I=1,N1
            X(I)=2.0*X(I)
   20       CONTINUE
            ND=INT(X(N1))+1
            IF (ND .LT.500) GO TO 24
            WRITE (6,21) II
   21       FORMAT(' '/20X,'SUB-PERIOD NO. ',I2,'  :NO. OF DATA PTS. >500')
            GO TO 60
   24       CALL DAY(X,Y,Q1,ND,K)
            WRITE(6,25)II,K
   25       FORMAT(' '/20X,'SUB-PERIOD NO. ',I2,'  :NO. OF DATA PTS.=',I3)
            DO 30 I=1,K
            J=J+1
            IF (J .LE. 999) GO TO 29
            WRITE (6,27)
   27       FORMAT (' '/20X,'TOTAL NO. OF DATA PTS. >1000')
            GO TO 60
   29       QQ(J)=Q1(I)
   30       CONTINUE
            J=J+1
            QQ(J)=-999.
   40       CONTINUE
            WRITE(6,26) J
   26       FORMAT(' '/20X,'TOTAL NO. OF DATA PTS.=',I4)
            WRITE(7,45) J
   45       FORMAT(' ',I6)
            WRITE(7,50) (QQ(I),I=1,J)
   50       FORMAT(' ',10F7.0)
            GO TO 65
   60       STOP 4
   65       STOP
            END

 STOP     0
12:09.15 .571 RC=0
```

```
1    C          SUBROUTINE "SUBDAY"
2    C
3    C     TO INTERPOLATE HYDROGRAPH CO-ORDINATES AT HALF-DAY INTERVALS.
4    C
5          SUBROUTINE DAY(X,Y,Q,ND,K)
6          DIMENSION X(500),Y(500),Q(500)
7          Q(1)=Y(1)
8          A=0.0
9          K=1
10         J=1
11         DO 10 I=2,ND
12         A=A+1.0
13   14    IF(A-X(J)) 20,20,15
14   15    J=J+1
15         GO TO 14
16   20    K=K+1
17         Q(K)=Y(J-1)+((A-X(J-1))*(Y(J)-Y(J-1))/(X(J)-X(J-1)))
18   10    CONTINUE
19         RETURN
20         END
```

```
1    C            SUBROUTINE "SORTROW"
2    C      TO REARRANGE ALL THE COLUMNS OF A TWO-DIMENSIONAL ARRAY, BY
3    C      ARRANGING A SELECTED ROW IN DESCENDING ORDER FROM LEFT TO RIGHT.
4    C
5    C      X=INPUT ARRAY TO BE REARRANGED :NO. OF ROWS = IROW
6    C                                      NO. OF COLUMNS=ICOL
7    C      NROW=NO. OF THE ROW TO BE ARRANGED IN DESCENDING ORDER.
8           SUBROUTINE SORTRO(X,IROW,ICOL,NROW)
9           DIMENSION X(2,5000),TEM(2)
10          L=0
11          DO 300 I=1,ICOL
12          L=L+1
13          TEMP=X(NROW,I)
14          DO 200 J=L,ICOL
15          IF (X(NROW,J).GE.TEMP) GO TO 100
16          GO TO 200
17   100    TEMP=X(NROW,J)
18          M=J
19   200    CONTINUE
20   250    DO 300 JJ=1,IROW
21          TEM(JJ)=X(JJ,M)
22          X(JJ,M)=X(JJ,I)
23          X(JJ,I)=TEM(JJ)
24   300    CONTINUE
25          RETURN
26          END
```

```
      C                PROGRAM "DRAW"
      C
      C     TO PLOT HYDROGRAPH ON SEMI-LOGRITHMIC AXES TO SCALES OF:-
      C     5.2INS/ LOG CYCLE FOR DISCHARGE,
      C     1.0INS/ DAY FOR TIME.
      C     MAX. PLOT LENGTH=36 INS.
      C
            DIMENSION ALPH(20),R(2),D(2),X(500),Y(500)
            READ (3,6) NSTART
            READ(3,3) (ALPH(I),I=1,20)
    3       FORMAT(1X,20A4)
            READ(3,5) D(1),D(2)
    5       FORMAT(1X,2F10.4)
            READ(3,6) L5
    6       FORMAT(1X,I6)
            READ(3,20) ((X(I),Y(I)),I=1,L5)
   20       FORMAT (7X,F12.4,F14.0)
            J=NSTART-1
      C
      C     REDUCE Y-VALUE RANGE TO 5 LOG CYCLES
            IF((D(2)-D(1)).LE. 5.0) GO TO 24
            D(1)=D(2)-5.0
            K=0
            DO 30 I=NSTART,L5
            IF (Y(I)-10.0**D(1)) 30,32,32
   32       K=K+1
            Y(K)=Y(I)
            X(K)=X(I)
   30       CONTINUE
            L5=K
            WRITE(6,34)
   34       FORMAT(' '////20X,'ORIGINAL Y-AXIS LENGTH EXCEEDS 26INS:'/21X,'Y-A
           *XIS REDUCED TO 5 LOG-CYCLES')
            GO TO 55
   24       L5=L5-J
            IF (NSTART.EQ.1) GO TO 55
            DO 50 I=1,L5
            J=J+1
            X(I)=X(J)
            Y(I)=Y(J)
   50       CONTINUE
      C
      C     REDUCE TIME SPAN TO 36 DAYS: DELETE LATER VALUES
   55       DO 40 I=1,L5
            IF ((X(I)-X(1)).GT. 36.0) GO TO 45
   40       CONTINUE
            GO TO 25
   45       L5=I-1
   25       HC=(X(L5)-X(1))+1.0
            VB=D(2)-D(1)
            VC=5.2*VB
            HA=AINT(X(1))
            CALL CGPL(X,Y,Y,L5,-1,1,2,N,1,HA,1.0,HC,D(1),VB,VC,ALPH,6)
            STOP
            END
```

APPENDIX II

HYDROGRAPH PARAMETERS

No.	W.S.C. Station No.	Rising Limb Slope		Falling Limb Slope		Base Flow: BF	Peak Flow from 1 ins. Excess Ppt: Q_o(1")
		Average: R(av)	Steepest: R(max)	Average: K(av)	Steepest: K(max)		
1	5AA023	.346	.179	.648	.648	30	4,686
2	5AB002	.0596	.00816	.257	.00231	0	22,116
3	5AC003	.0154	.000918	.132	.005	0	38,732
4	5AD008	.104	.00229	.402	.099	10	11,793
5	5AD019	.176	.064	.422	.37	10	53,357
6	5AH005	.0345	.0000356	.104	.0413	0	26,987
7	5BL009	.14	.14	.414	.414	20	14,882
8	5BL020	.134	.033	.522	.194	0	8,689
9	5CH001	.256	.256	.55	.406	200	11,628
10	5CB001	.030	.00038	.375	.23	0	18,980
11	5CC007	.067	.00088	.312	.23	0	16,449
12	5CE002	.0435	.0000565	.0688	.0148	0	36,760
13	5CE005	.0052	.000157	.55	.316	0	18,594

TABLE II-I PARAMETERS OBTAINED FROM COMPOSITE HYDROGRAPHS

No.	W.S.C. Station No.	Rising Limb Slope		Falling Limb Slope		Base Flow: BF	Peak Flow from 1 ins. Excess Ppt: Q_o(1")
		Average: R(av)	Steepest: R(max)	Average: K(av)	Steepest: K(max)		
14	5DB001	.284	.157	.467	.269	150	16,234
15	5DC002	.375	.376	.494	.304	250	23,143
16	5EA001	.0477	.000238	.337	.0086	0	28,131
17	5EE001	.157	.00071	.421	.244	0	34,764
18	5FA001	.132	.00465	.389	.00334	0	12,270
19	5FD001	.0542	.00077	.276	.0512	0	23,693
20	5FE001	.0862	.000123	.464	.167	0	158,266
21	5GA003	.0161	.000061	.437	.112	0	10,441
22	6AD006	.492	.259	.771	.638	10	27,902
23	7AB001	.605	.54	.494	.298	40	7,413
24	7AD001	.395	.0927	.598	.458	200	35,960
25	7AF002	.107	.107	.195	.0388	20	25,656
26	7AH001	.309	.0694	.37	.223	0	9,553

TABLE II-I (CONT.) PARAMETERS OBTAINED FROM COMPOSITE HYDROGRAPHS

No.	W.S.C. Station No.	Rising Limb Slope		Falling Limb Slope		Base Flow: BF	Peak Flow from 1 ins. Excess Ppt: Q_o(1")
		Average: R(av)	Steepest: R(max)	Average: K(av)	Steepest: K(max)		
27	7BH001	.184	.0743	.272	.075	10	21,950
28	7BB003	.18	.0133	.45	.088	0	9,783
29	7BC002	.242	.129	.49	.049	20	57,983
30	7BF001	.0137	.000622	.212	.00685	0	15,266
31	7BJ001	.0096	.000173	.253	.0533	10	21,148
32	7BK001	.75	.75	.634	.375	200	N/A
33	7BK005	.354	.151	.404	.00012	10	13,416
34	7CD001	.496	.254	.572	.42	1,500	106,114
35	7GE001	.175	.0182	.239	.0862	100	91,961
36	7GF001	.136	.0167	.303	.134	40	38,609
37	7GH002	.125	.0249	.437	.155	25	65,656
38	7HA003	.0945	.072	.368	.00816	0	14,245
39	7HC001	.0726	.0726	.277	.0745	0	41,808

TABLE II-I (CONT.) PARAMETERS OBTAINED FROM COMPOSITE HYDROGRAPHS

No.	W.S.C. Station No.	Rising Limb Slope		Falling Limb Slope		Base Flow: BF	Peak Flow from 1 ins. Excess Ppt: Q_o(1")
		Average: R(av)	Steepest: R(max)	Average: K(av)	Steepest: K(max)		
40	7JF002	.102	.0229	.348	.0152	0	46,813
41	8AA003	.42	.42	.733	.582	500	21,972
42	9AA007	.798	.588	.974	.845	40	N/A
43	9AB008	.612	.45	.788	.758	100	3,004
44	9AC001	.590	.413	.904	.853	250	N/A
45	9AC004	.642	.352	.949	.949	150	N/A
46	9AE001	.79	.656	.97	.97	1,500	N/A
47	9AG001	.455	.0141	.736	.654	500	17,859
48	9BA001	.259	.0732	.54	.102	250	33,221
49	9BC002	.218	.0598	.66	.509	400	69,560
50	9DC002	.544	.373	.564	.206	1,000	101,268
51	9DD002	.55	.45	.78	.704	1,000	68,670
52	9EA003	.542	.218	.69	.594	200	19,753

TABLE II-1 (CONT.) PARAMETERS OBTAINED FROM COMPOSITE HYDROGRAPHS

No.	W.S.C. Station No.	Rising Limb Slope		Falling Limb Slope		Base Flow: BF	Peak Flow from 1 ins. Excess Ppt: Q_o(1")
		Average: R(av)	Steepest: R(max)	Average: K(av)	Steepest: K(max)		
53	10AA001	.534	.296	.70	.57	2,000	85,478
54	10AB001	.774	.38	.94	.94	600	8,272
55	10EA003	.0714	.0222	.707	.56	200	28,124
56	10EB001	.325	.0436	.603	.55	1,000	57,809
57	10EC001	.342	.0503	.727	.526	1,500	92,548
58	10GB001	.50	.255	.742	.538	150	47,581
59	10HB001	.702	.266	.638	.605	500	34,854
60	10MA001	.447	.212	.633	.494	2,000	89,116
61	11AA005	.216	.0054	.36	.301	10	17,142
62	11AA031	.0127	.000364	.184	.00137	0	85,981

TABLE II-I (CONT.) PARAMETERS OBTAINED FROM COMPOSITE HYDROGRAPHS

No.	W.S.C. Station No.	Rising Limb Slope		Falling Limb Slope		Base Flow: BF	Peak Flow from 1 ins. Excess Ppt: Q_o(1")
		Average: R(av)	Steepest: R(max)	Average: K(av)	Steepest: K(max)		
63	Lucky Cr.	0.54		0.54		0	549
64	Upper Tom Cr.	0.025		0.24		0	190
65	Moore Cr.	0.013		0.16		0	211
66	Spencer Cr.	0.31		0.35		0	893
67	Burnt Cr.	0.13		0.06		0	139
68	Tom Cr.	0.28		0.85		0	637
69	Bear Cr.	0.08		0.41		0	26
70	Watson Cr.	0.62		0.64		0	230

TABLE II-2 HYDROGRAPH PARAMETERS FOR ADDITIONAL SMALL BASINS

APPENDIX III

DRAINAGE BASIN CHARACTERISTICS

Parameter No.	No.	1	2	3	4	5
	W.S.C. Station No.	5AA023	5AB002	5AC003	5AD008	5AD019
	Station Name	Oldman R. nr. Waldron's CNR	Willow Cr. nr. Nolan	Little Bow R. @ Carmangay	Waterton R. nr. Standoff	Oldman R. nr. Monarch
1	TDA.	551	900	1,060	674	3,450
2	LA.	0	0	10	0.7	0.3
3	FA.	95	45	5	70	44
4	MCL.	40	40	68	65	108
5	BSF.	2.9	1.8	4.6	6.3	3.3
6	BA.(x)	0	0.7	0.7	0.7	1.0
7	BA.(y)	-1.0	-0.7	-0.7	0.7	0
8	DE.	8,500	7,800	4,500	7,500	8,500
9	GE.	4,100	3,140	2,950	3,320	2,920
10	ME.	10,100	7,900	4,500	9,000	10,100
11	RE.	6,000	4,760	1,550	5,680	7,180
12	BE.	5,025	3,845	3,315	4,175	4,115
13	MCS.	51.5	43.6	13.1	34.0	28.0
14	LAT.	49.81	49.79	50.13	49.50	49.79
15	RAIN	1.1	1.3	1.5	1.3	1.4
	REGION	F	F	P	F	P

F = Foothills; P = Prairies; A = Aspen Parkland; B = Boreal Forest; YT = Yukon or N.W.T.

TABLE III-I DRAINAGE BASIN CHARACTERISTICS

Parameter No.	No.	6	7	8	9	10
	W.S.C. Station No.	5AH005	5BL009	5BL020	5CA001	5CB001
	Station Name	7 Persons Cr. @ Medicine Hat	Highwood R. nr. Aldersyde	Sheep R. nr. Aldersyde	Red Deer R. nr. Sundre	Little Red Deer R. @ Mouth
1	TDA.	744	906	660	954	924
2	LA.	0.2	0	0	0	0.5
3	FA	0	44	60	60	70
4	MCL.	90	65	60	72	172
5	BSF	10.9	4.7	5.4	5.2	31.8
6	BA.(x)	0.7	0.7	1.0	1.0	0.7
7	BA.(y)	0.7	0.7	0	0	0.7
8	DE.	4,800	8,000	10,600	10,000	5,500
9	GE.	2,200	3,400	3,320	3,900	3,00
10	ME.	4,800	10,100	10,600	10,000	5,500
11	RE.	2,600	6,700	7,280	6,100	2,500
12	BE.	2,850	4,625	4,500	5,075	3,675
13	MCS.	13.2	46.0	45.0	34.3	8.1
14	LAT.	50.02	50.70	50.71	51.70	52.02
15	RAIN	1.5	1.4	1.4	1.2	1.4
	REGION	P	F	F	F	A

TABLE III-1 (CONT) DRAINAGE BASIN CHARACTERISTICS

Parameter No.	No.	11	12	13	14	15
	W.S.C. Station No.	5CC007	5CE002	5CE005	5DB001	5DC002
	Station Name	Medicine R. nr. Eckville	Kneehills Cr. nr. Drumheller	Rosebud R. @ Redland	Clearwater R. nr. Rocky Mtn.Hse.	N. Saskn. @ Saunders
1	TDA.	754	950	1,400	1,210	1,980
2	LA.	10.5	0	0.7	0	0.2
3	FA.	55	9	5	95	75
4	MCL.	51	72	120	105	88
5	BSF	3.4	5.5	10.3	9.1	4.0
6	BA.(x)	0.7	0.7	0.7	0.7	1.0
7	BA.(y)	-0.7	-0.7	-0.7	0.7	0
8	DE.	3,350	3,275	3,600	9,500	9,000
9	GE.	3,000	2,180	2,600	3,150	3,700
10	ME.	3,460	3,325	3,600	11,000	11,400
11	RE.	460	1,145	1,000	7,850	7,700
12	BE.	3,230	2,680	3,030	4,550	4,450
13	MCS.	2.6	8.4	7.3	32.0	7.6
14	LAT.	52.32	51.49	51.29	52.34	52.45
15	RAIN	1.5	1.6	1.6	1.4	1.2
	REGION	A	P	P	F	F

TABLE III-I (CONT) DRAINAGE BASIN CHARACTERISTICS

Parameter No.	No.	16	17	18	19	20
	W.S.C. Station No.	5EA001	5EE001	5FA001	5FD001	5FE001
	Station Name	Sturgeon R. nr. Ft. Saskn.	Vermilion R. nr. Mannville	Battle R. nr. Ponoka	Ribstone Cr. nr. Edgerton	Battle R. nr. Unwin
1	TDA.	1,310	2,200	711	990	10,100
2	LA.	4.3	4.8	0.7	16	5
3	FA.	25	13	50	18	20
4	MCL.	126	122	52	87	354
5	BSF.	12.1	6.7	3.8	7.7	12.5
6	BA.(x)	1.0	1.0	0.7	0.7	1.0
7	BA.(y)	0	0	-0.7	0.7	0
8	DE.	2,600	2,350	3,200	2,610	3,010
9	GE.	2,000	1,905	2,650	2,065	1,750
10	ME.	2,700	2,350	3,200	2,620	3,125
11	RE.	700	445	550	555	1,375
12	BE.	2,210	2,090	2,705	2,245	2,195
13	MCS.	3.4	2.6	2.3	3.3	2.0
14	LAT.	53.79	53.38	52.66	52.75	52.95
15	RAIN	1.8	1.7	1.8	1.7	1.7
	REGION	A	A	A	A	A

TABLE III-1 (CONT) DRAINAGE BASIN CHARACTERISTICS

Parameter No.	No.	21	22	23	24	25
	W.S.C. Station No.	5GA003	6AD006	7AB001	7AD001	7AF002
	Station Name	Monitor Cr. nr. Monitor	Beaver R. @ Cold Lake Res.	Snake Indian nr. Bedson	Athabasca R. @ Entrance	McLeod R. above Embarras R.
1	TDA.	565	5,460	911	3,915	1,010
2	LA.	2.1	5	.3	0.6	0.5
3	FA.	0	80	60	60	90
4	MCL.	41	155	60	108	92
5	BSF.	7.3	4.4	3.9	3.0	8.4
6	BA.(x)	0.7	0.7	0.7	-0.7	0.7
7	BA.(y)	0.7	-0.7	-0.7	0.7	0.7
8	DE.	2,600	2,300	8,000	12,300	6,500
9	GE.	2,200	1,650	3,500	3,250	3,100
10	ME.	2,600	2,500	9,640	12,300	8,530
11	RE.	400	850	6,140	9,050	5,430
12	BE.	2,395	1,920	4,750	3,890	3,975
13	MCS.	7.6	3.2	44.4	15.1	41.0
14	LAT.	51.97	54.36	53.17	53.38	53.47
15	RAIN	1.7	1.4	1.1	1.2	1.4
	REGION	P	B	F	F	F

TABLE III-I (CONT) DRAINAGE BASIN CHARACTERISTICS

Parameter No.	No.	26	27	28	29	30
	W.S.C. Station No.	7AH001	7BA001	7BB003	7BC002	7BF001
	Station Name	Freeman R. nr. Ft. Assiniboine	Pembina R. Below Paddy Cr.	Lobstick R. nr. Styal	Pembina R. @ Jarvie	E.Prairie R. nr. Enilda
1	TDA.	662	1,110	670	4,550	500
2	LA.	0	0.5	6.5	1.5	6
3	FA.	99	98	6.5	95	98
4	MCL.	104	180	64	400	85
5	BSF.	16.3	29.2	5.5	35.2	19.5
6	BA.(x)	1.0	1.0	1.0	0.7	-0.7
7	BA.(y)	0	0	0	0.7	0.7
8	DE.	3,800	7,500	3,400	7,500	4,475
9	GE,	2,000	2,760	2,500	2,000	1,940
10	ME.	3,800	7,850	3,400	7,850	4,475
11	RE.	1,800	5,090	900	5,850	2,535
12	BE.	2,800	3,700	2,745	3,025	2,370
13	MCS.	11.5	11.9	8.5	6.5	9.4
14	LAT.	54.36	53.13	53.14	54.45	55.42
15	RAIN	1.5	1.5	1.6	1.5	1.1
	REGION	B	B	B	B	B

TABLE III-I (CONT) DRAINAGE BASIN CHARACTERISTICS

Parameter No.	No.	31	32	33	34	35
	W.S.C. Station No.	7BJ001	7BK001	7BK005	7CD001	7GE001
	Station Name	Swan R. nr. Kinuso	L. Slave R. @ Slave Lake	Saulteaux R. nr. Spurfield	Clearwater R. @ Draper	Wapiti R. nr. Gande Prairie
1	TDA.	742	5,370	1,030	11,800	4,350
2	LA.	0	20	1.0	1.7	0
3	FA.	98	80	98	98	95
4	MCL.	64	180	112	288	128
5	BSF.	5.5	6	11.8	7.0	4.7
6	BA.(x)	0	0.7	0.7	-1.0	1.0
7	BA.(y)	1.0	-0.7	0.7	0	0
8	DE.	4,400	2,300	4,000	1,800	4,500
9	GE.	1,940	1,850	1,920	800	1,700
10	ME.	4,400	4,300	4,000	1,900	7,600
11	RE.	2,460	2,450	2,080	1,100	5,900
12	BE.	3,285	2,000	2,290	1,220	2,775
13	MCS.	25.7	2.2	6.4	3.5	20.3
14	LAT.	55.33	55.30	55.16	56.67	55.71
15	RAIN	1.2	1.2	1.2	0.9	1.2
	REGION	B	B	B	B	F

TABLE III-I (CONT) DRAINAGE BASIN CHARACTERISTICS

Parameter No.	No.	36	37	38	39	40
	W.S.C. Station No.	7GF001	7GH002	7HA003	7HC001	07JF002
	Station Name	Simonette R. nr. Goodwin	L. Smokey R. nr. Guy	Heart R. nr. Nampa	Notikewin R. @ Manning	Boyer R. nr. Ft.Vermillion
1	TDA.	1,920	4,130	757	1,810	2,420
2	LA.	0	1.5	21.5	2	3.5
3	FA.	99	98	90	98	96
4	MCL.	172	260	57	153	100
5	BSF.	15.4	16.4	4.3	13	4.1
6	BA.(x)	0	0	-1.0	1.0	0.7
7	BA.(y)	1.0	1.0	0	0	0.7
8	DE.	5,000	5,000	2,400	3,520	1,500
9	GE.	1,640	1,600	1,820	1,490	890
10	ME.	5,000	5,000	2,500	3,575	1,573
11	RE.	2,360	2,400	680	2,085	683
12	BE.	2,750	2,750	2,070	2,105	1,085
13	MCS.	15.5	9.2	7.2	6.2	3.5
14	LAT.	55.14	55.46	56.17	56.92	58.44
15	RAIN	1.2	0.9	1.0	0.9	0.7
	REGION	B	B	B	B	B

TABLE III-1 (CONT) DRAINAGE BASIN CHARACTERISTICS

Parameter No.	No.	41	42	43	44	45
	W.S.C. Station No.	8AA003	9AA007	9AB008	9AC001	9AC004
	Station Name	Dezadeach R. @ Haines Jnctn.	Lubbock R. nr. Atlin	M'Clintock R. nr. Whitehorse	Takhini R. nr. Whitehorse	Takhini R. @ Outlet Kusawa L
1	TDA.	3,200	650	597	2,640	1,570
2	LA.	4.3	4.5	2.1	4.9	7.8
3	FA.	62.9	95	81	36	25
4	MCL.	144	24	40	112	80
5	BSF	6.5	0.9	2.7	4.8	4.1
6	BA.(x)	-0.7	0	0	0	0.7
7	BA.(y)	-0.7	-0.1	-1.0	1.0	0.7
8	DE.	3,500	2,400	2,500	5,500	5,500
9	GE.	1,930	2,200	2,350	2,150	2,200
10	ME.	7,625	6,389	6,880	8,275	8,275
11	RE.	5,695	4,189	4,530	6,125	6,075
12	BE.	2,125	2,331	2,450	2,725	3,100
13	MCS.	2.2	6.6	2.9	9.4	22.5
14	LAT.	60.75	60.08	60.61	60.85	60.61
15	RAIN	0.5	0.6	0.5	0.5	0.5
	REGION	YT	YT	YT	YT	YT

TABLE III-1 (CONT) DRAINAGE BASIN CHARACTERISTICS

Parameter No.	No.	46	47	48	49	50
	W.S.C. Station No.	9AE001	9AG001	9BA001	9BC002	9DC002
	Station Name	Teslin R. nr. Teslin	Big Salmon R. nr. Carmacks	Ross River @ Ross River	Pelly R. @ Ross River	Stewart R. @ Mayo
1	TDA.	11,700	2,640	2,800	7,670	12,100
2	LA.	3.8	0.8	1.8	1.4	1.0
3	FA.	65	68	89	82	82
4	MCL.	162	144	176	208	280
5	BSF.	2.2	7.9	11.1	5.7	6.5
6	BA.(x)	-0.7	-0.7	-0.7	-0.7	-0.7
7	BA.(y)	0.7	0.7	-0.7	0.7	-0.7
8	DE.	5,000	2,900	6,500	5,500	6,000
9	GE.	2,240	1,800	2,350	2,295	2,200
10	ME.	7,160	7,350	7,470	7,470	7,360
11	RE.	4,920	5,550	5,170	5,175	5,160
12	BE.	2,520	2,265	2,865	3,005	2,525
13	MCS.	3.5	6.0	5.5	7.9	2.4
14	LAT.	60.48	61.88	61.99	61.99	63.59
15	RAIN	0.6	0.5	0.6	0.6	0.5
	REGION	YT	YT	YT	YT	YT

TABLE III-1 (CONT) DRAINAGE BASIN CHARACTERISTICS

Parameter No.	No.	51	52	53	54	55
	W.S.C. Station No.	9DDD002	9EA003	10AA001	10AB001	10EA003
	Station Name	Stewart R. @ Stewart Xing	Klondike R. above Bonanza Cr.	Liard R. @ Upper Xing	Frances R. nr. Watson L.	Flat R. @ Mouth
1	TDA.	13,500	3,010	12,500	4,570	3,280
2	LA.	0.8	0	1.5	2.6	0.2
3	FA.	85	65	84	75	78
4	MCL.	318	134	196	180	162
5	BSF	7.5	4.4	3.1	7.1	6.9
6	BA.(x)	-0.7	-1.0	0.7	0	0.7
7	BA.(y)	-0.7	0	-0.7	-1.0	-0.7
8	DE.	6,000	4,000	6,000	7,000	4,000
9	GE	1,850	1,100	1,990	2,265	1,500
10	ME.	7,360	6,400	7,780	7,780	8,300
11	RE.	5,510	5,300	5,790	5,525	6,800
12	BE.	2,515	1,900	2,700	2,425	2,500
13	MCS.	3.9	7.5	8.2	1.9	12.2
14	LAT.	63.38	64.04	60.05	60.45	61.53
15	RAIN	0.5	0.5	0.6	0.6	0.6
	REGION	YT	YT	YT	YT	YT

TABLE III-1 (CONT) DRAINAGE BASIN CHARACTERISTICS

Parameter No.	No.	56	57	58	59	60
	W.S.C. Station No.	10EB001	10EC001	10GB001	10HB001	10MA001
	Station Name	S. Nahanni R. above Virginia Falls	S. Nahanni R. above Calusen Cr.	Willowlake R. nr. Mouth	Redstone R. nr. Mouth	Peel R. above Canyon Cr.
1	TDA.	5,650	12,900	8,330	6,080	10,200
2	LA.	1.1	0.5	22	0.5	0.1
3	FA.	45	75	66	45	26
4	MCL	208	286	180	180	160
5	BSF	7.7	6.3	3.9	5.3	2.5
6	BA.(x)	0.7	0.7	-1.0	0.7	0.7
7	BA.(y)	-0.7	-0.7	0	0.7	0.7
8	DE.	6,000	6,000	750	7,000	5,500
9	GE.	1,600	850	450	400	1,250
10	ME.	9,100	9,100	2,500	8,900	7,760
11	RE.	7,500	8,250	2,050	8,500	6,510
12	BE.	2,615	2,050	565	2,000	2,250
13	MCS.	8.4	6.1	1.2	17.7	16.5
14	LAT.	61.63	61.25	62.65	64.18	65.89
15	RAIN	0.6	0.6	0.6	0.5	0.5
	REGION	YT	YT	YT	YT	YT

TABLE III-I (CONT) DRAINAGE BASIN CHARACTERISTICS

Parameter No.	No.	61	62	63	64	65
	W.S.C. Station No.	11AA005	11AA031			
	Station Name	Milk River @ Milk River	Milk River @ Intntl. Bndr.	Lucky Cr.	Upper tom Cr.	Moore Cr.
1	TDA.	1,040	2,630	66.5	6.9	8.1
2	LA.	0	0	0.13	0.22	0.08
3	FA.	2	1	98	97	61
4	MCL.	136	240	17.2	2.6	8.9
5	BSF.	17.8	21.8	4.66	1.88	3.3
6	BA.(x)	0.7	0.7	0.0	-1.0	-1.0
7	BA.(y)	0.7	0.7	1.0	-0.7	0.0
8	DE.	8,500	8,500	5,000	4,400	5,900
9	GE.	3,420	2,730	2,250	2,350	3,100
10	ME.	8,900	8,900	5,500	4,500	5,900
11	RE.	5,580	6,170	3,250	2,150	2,800
12	BE.	3,895	3,435	2,825	2,500	4,280
13	MCS.	7.9	7.4	83.3	297	420
14	LAT.	49.15	48.98	60.62	60.50	60.08
15	RAIN	1.3	1.3	0.6	0.6	0.6
	REGION	P	P	YT	YT	YT

TABLE III-1 (CONT) DRAINAGE BASIN CHARACTERISTICS

Parameter No.	No.	66	67	68	69	70
	W.S.C. Station No.					
	Station Name	Spencer Cr.	Burnt Cr.	Tom Cr.	Beer Cr.	Watson Cr.
1	TDA.	60.0	4.4	165	1.5	37.2
2	LA.	0.30	0.14	1.29	0	1.37
3	FA.	77	99	98	99	91
4	MCL.	16.1	3.0	28.7	1.6	13.2
5	BSF	4.4	3.1	5.2	2.7	5.12
6	BA.(x)	-0.7	-0.7	-0.7	-0.7	-0.7
7	BA.(y)	0.7	0.0	-0.7	0.7	0.7
8	DE.	6,300	4,000	4,100	2,700	3,900
9	GE.	2,800	2,700	2,395	2,450	2,240
10	ME.	6,670	4,000	5,180	2,700	3,912
11	RE.	3,870	1,300	2,785	250	1,670
12	BE.	3,615	3,125	2,750	2,585	2,545
13	MCS.	99	204	25.3	200	53.1
14	LAT.	60.16	60.20	60.30	60.30	60.10
15	RAIN	0.6	0.6	0.6	0.6	0.6
	REGION	YT	YT	YT	YT	YT

TABLE III-1 (CONT) DRAINAGE BASIN CHARACTERISTICS

APPENDIX IV

MAP COEFFICIENTS FOR

R(av), K(av), BF and PEAK FLOW

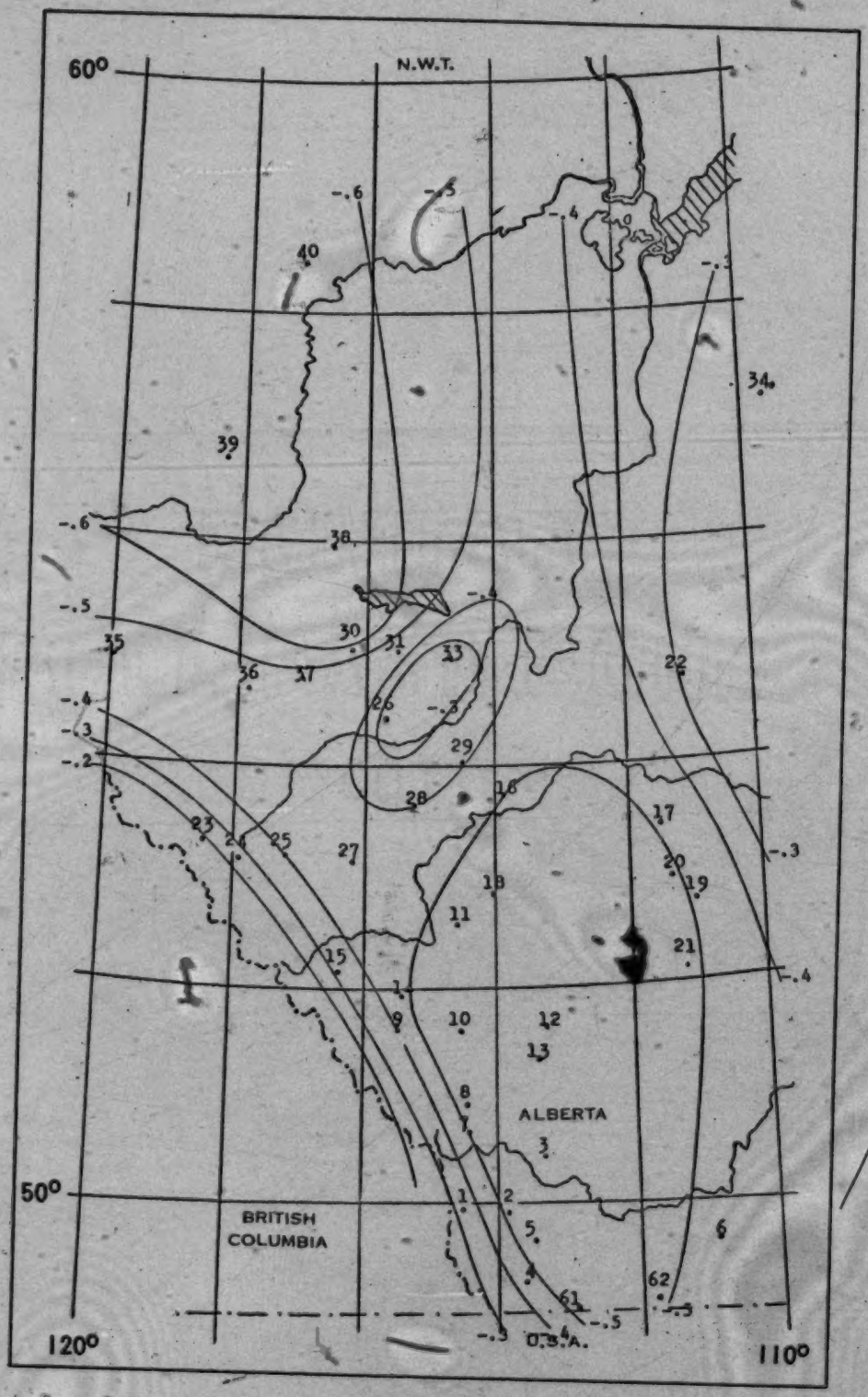


FIG. IV-1 MAP COEFFICIENTS FOR R (av)
FOR USE WITH EQUATION 4·11

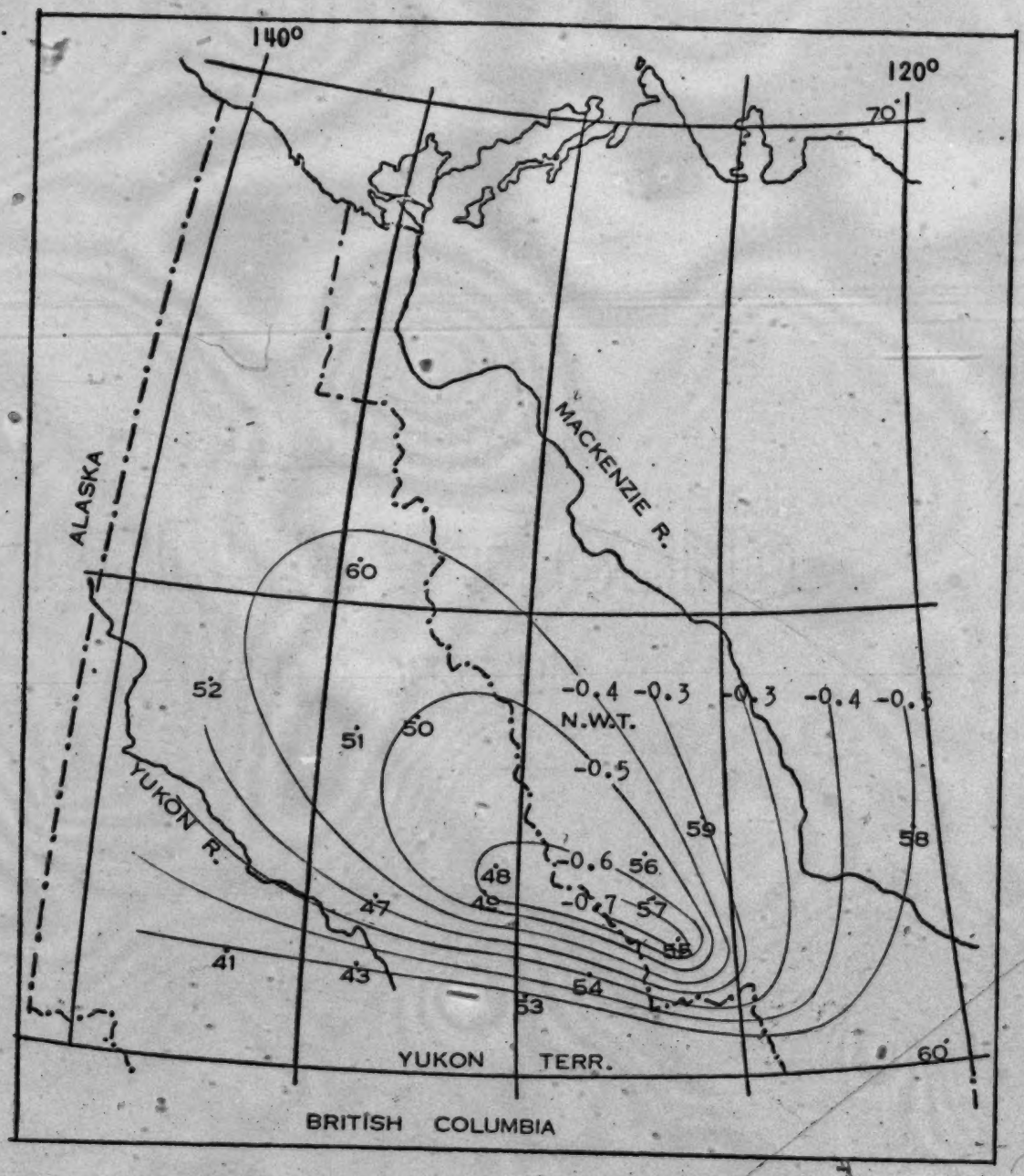


FIG. IV-2 MAP COEFFICIENTS FOR $R_{.}$(av) FOR USE WITH EQUATION 4·11

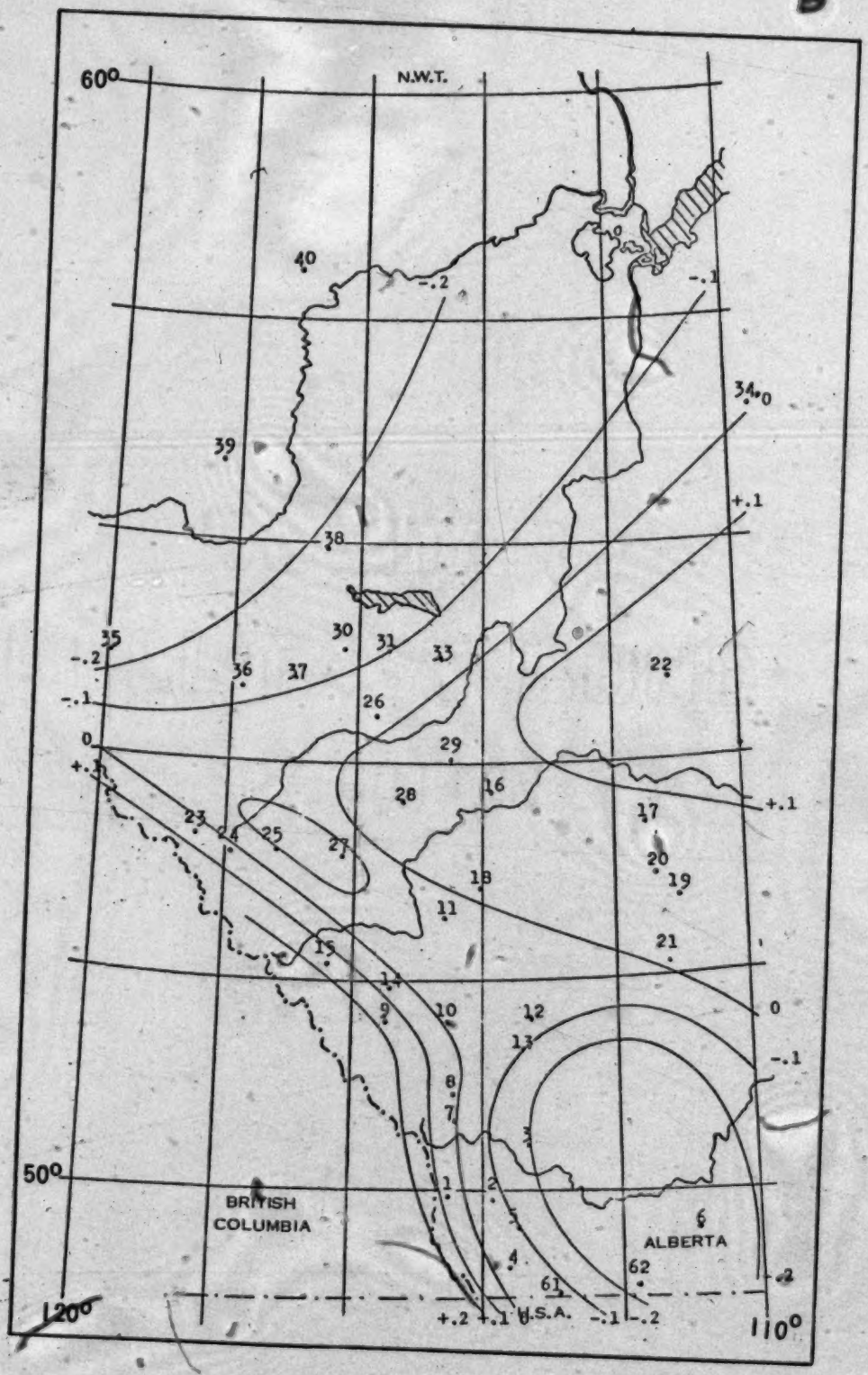


FIG. IV-3 MAP COEFFS FOR K (av) FOR USE WITH EQUATION 4·12

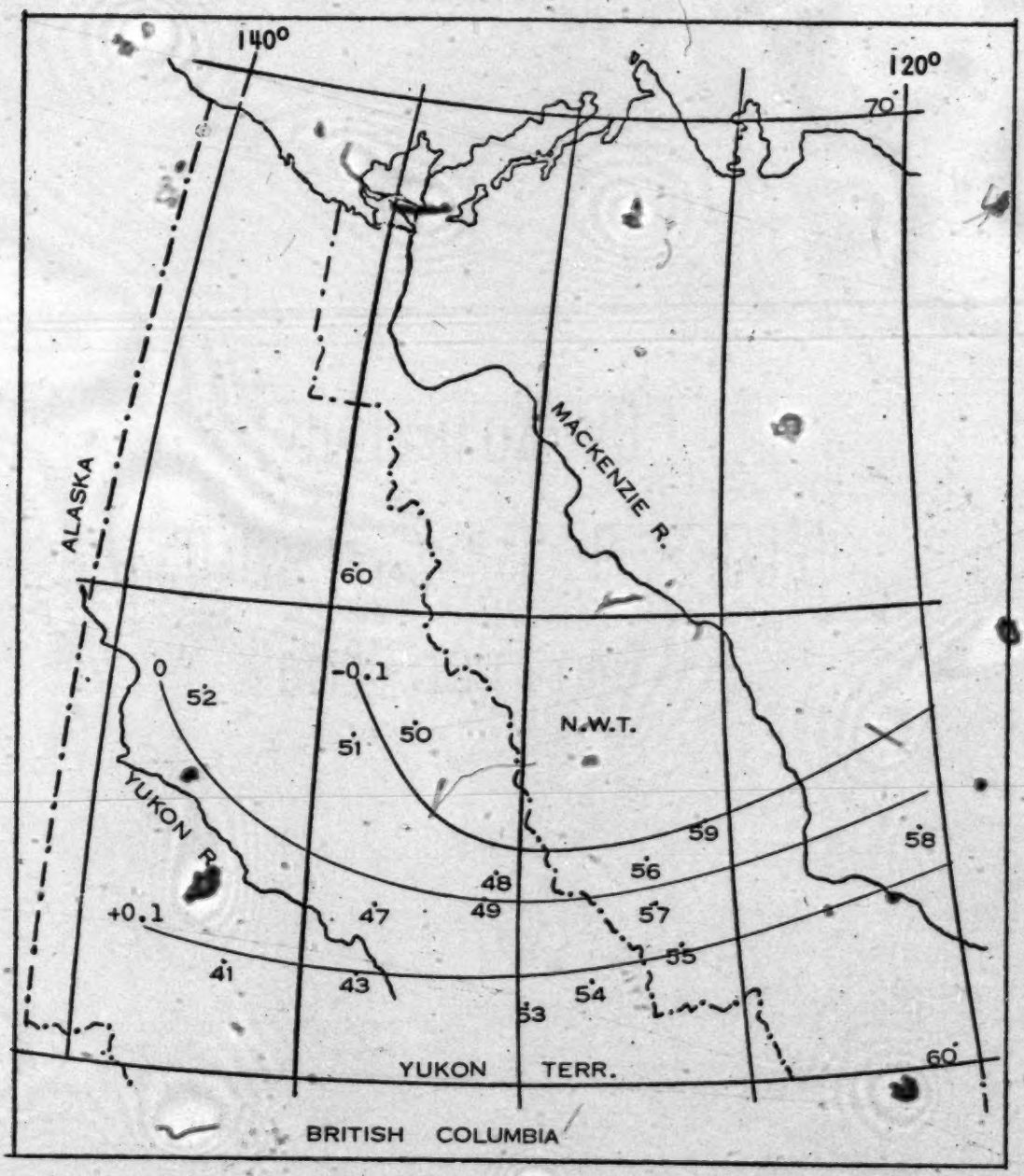


FIG. IV-4 MAP COEFFICIENTS FOR K (av) FOR USE WITH EQUATION 4·12

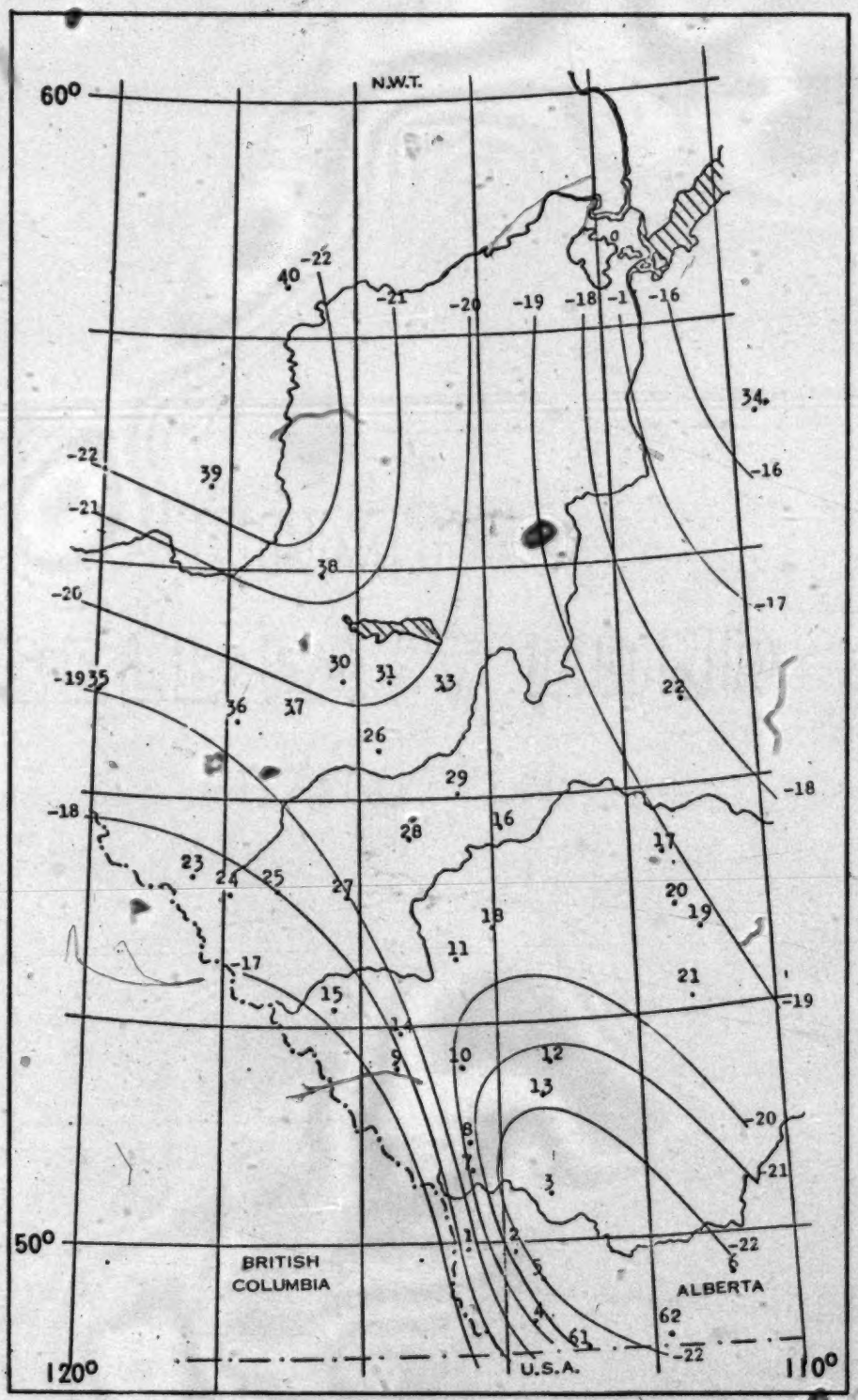


FIG. IV-5 MAP COEFFS FOR BASEFLOW (BF) FOR USE WITH EQUATION 4·13

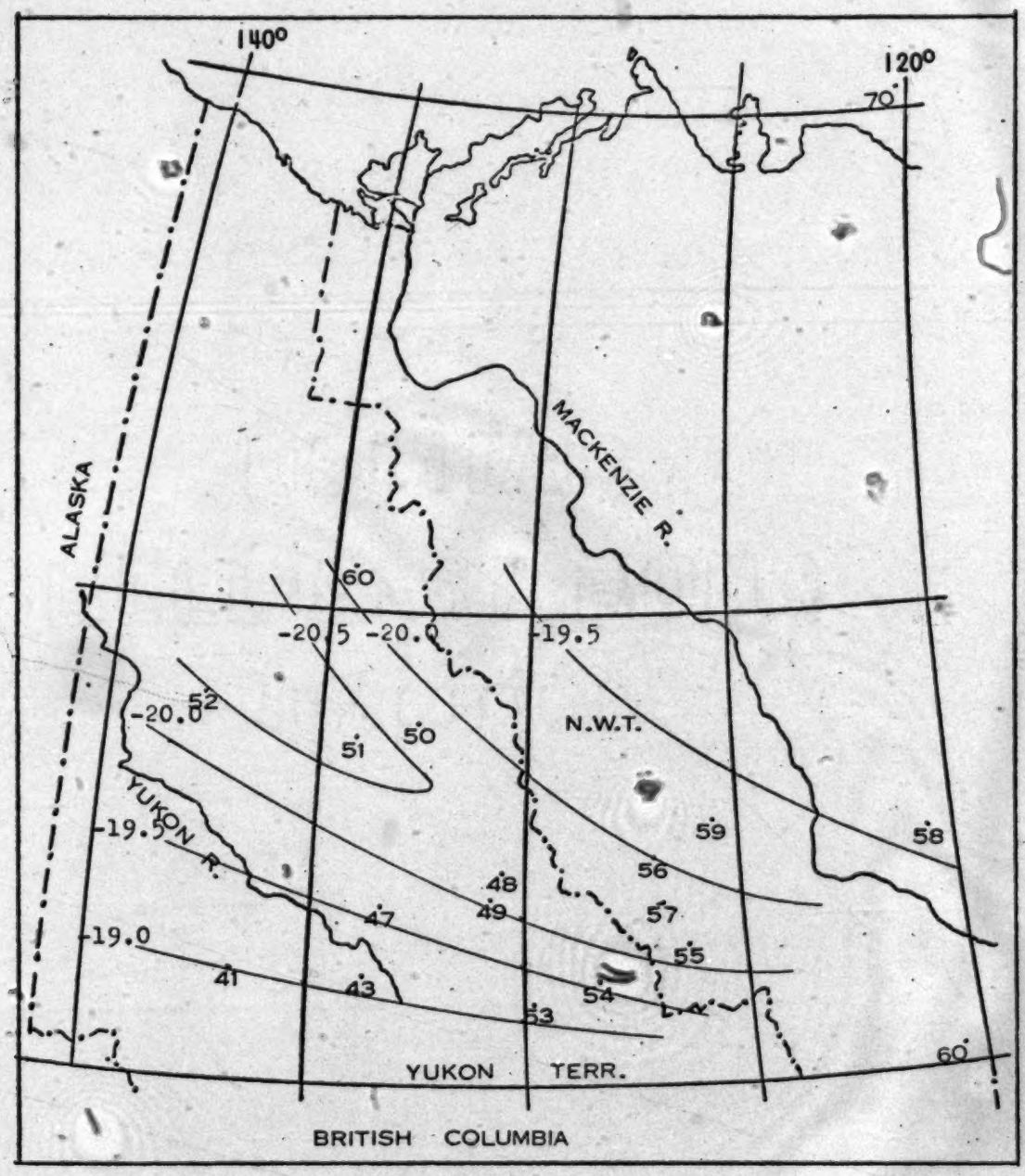


FIG. IV-6 MAP COEFFICIENTS FOR BASEFLOW (BF) FOR USE WITH EQUATION 4·13

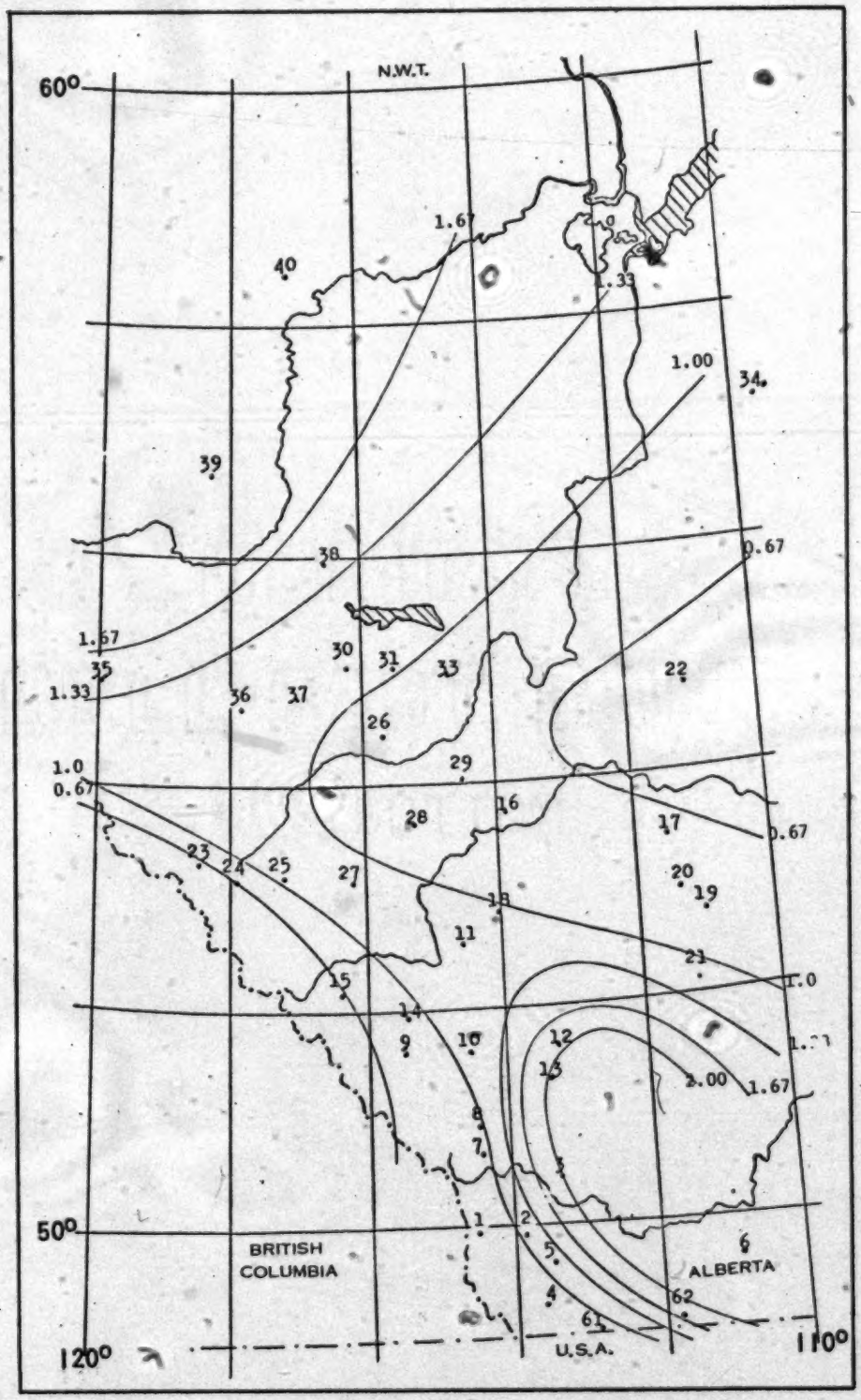


FIG. IV-7 MAP COEFFICIENTS FOR PEAK FLOW (Qo) FOR USE WITH EQUATIONS 5·10 TO 5·15 (FOR 0·1 TO 10 INS OF EXCESS PRECIPITATION)

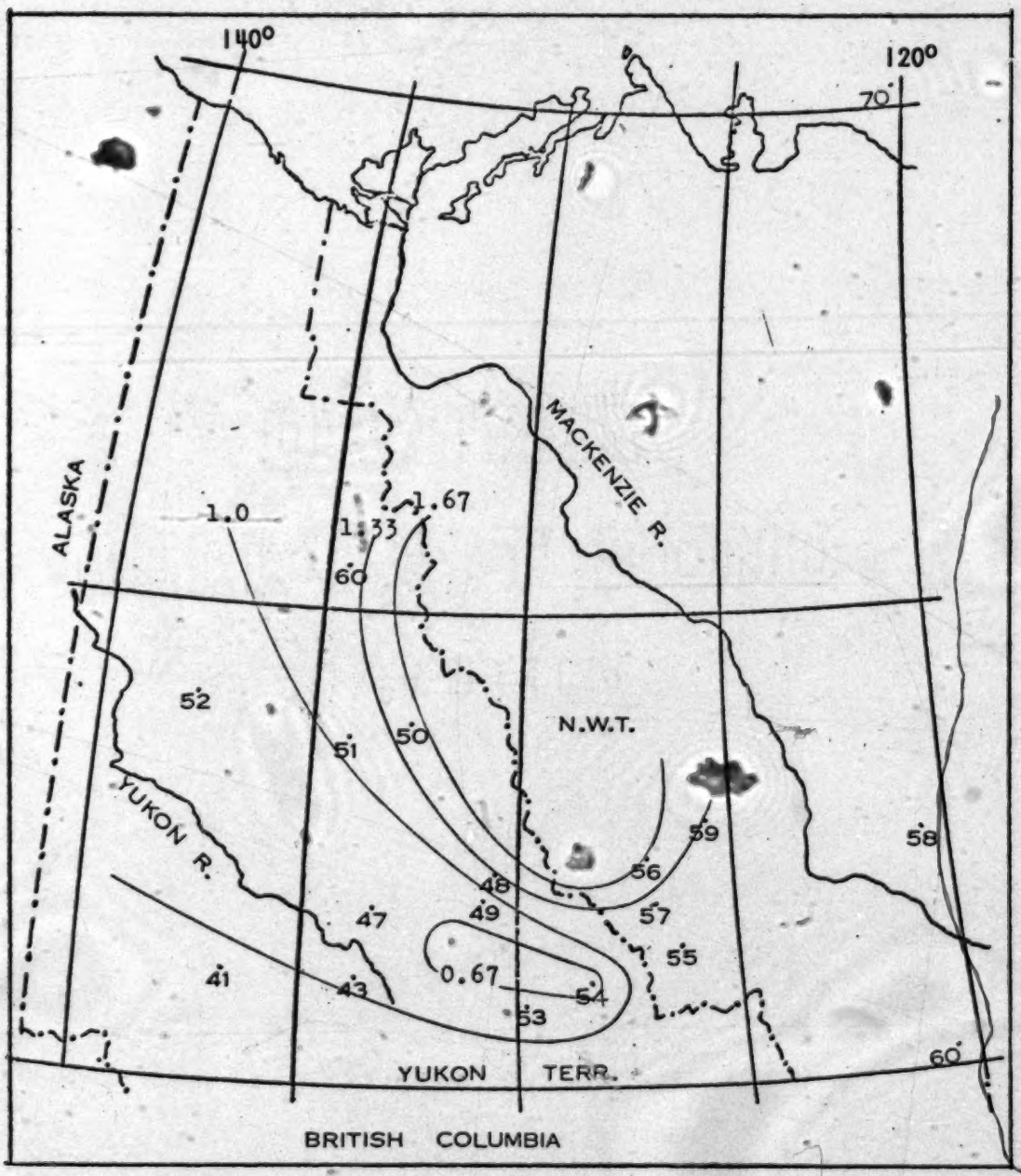


FIG. IV-8 MAP COEFFICIENTS FOR PEAK FLOW (Qo) FOR USE WITH EQUATIONS 5·10 TO 5·15 (0·1 - 10 INS OF EXCESS PRECIPITATION)